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DEVELOPMENT OF STEEL PLATE REQUIREMENTS FOR FIXED OFFSHORE STRUCTURES

PART 2

DRAFT REPORT *

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1. INTRODUCTION

Results of the DnV study "Development of Steel Plate Requirements for Fixed Offshore Structures" (Part 1), commissioned by the Centre for Frontier Engineering Research (CFER), have been discussed in detail by the members of the CSA Working Group on Materials. As a consequence of these discussions, it was felt that additional work was needed to supplement the report with the following objectives:

- To modify Figs. 1* to 3* of the original report† to provide CVN energy requirements for the whole range of plate thicknesses and design temperatures;

- To provide design temperature input for the Canadian East Coast offshore scenarios and demonstrate the relevant toughness requirements for use of structural steels;

- To show applicability of CSA steels (CSA CAN3-G40.21-M81) based on recommended toughness requirements;

- To discuss further effect of PWHT on the toughness requirements;

- To investigate whether more suitable graphical representation of the toughness requirements is possible;

- To discuss further application of fracture mechanics in the material design (crack initiation and crack arrest philosophy).

This supplement (Part 2) is therefore a not self-contained document, but rather an extension of the original report.

† Figures from the original report (Part 1) will be marked by an asterisk, (*). The original report will be referred to simply as the First Report.

2. PROPOSED REQUIREMENTS FOR STEEL PLATES

2.1 BACKGROUND COMMENTS

The toughness requirements for base plates proposed herein for primary applications (special I A and primary I B, as defined in Section 2.2) are based on the CVN test. Minimum CVN energy and CVN lateral expansion are proposed for structural steel plates. The CVN energy requirements are based on experience with welded steel structures in service, such as ships, pressure vessels and offshore structures.

The CVN toughness requirements account for the degradation of the weldable structural steels in the Heat Affected Zone (HAZ) and for the effect of the residual welding stresses introduced in the base material.

Critical to the application of the requirements, as they are presented in the chart (Fig. 1), is the definition of the design temperature. The design temperature determines the point in the chart at which the requirements can be obtained for a particular offshore location.

It is recommended that the CVN energy requirement for plates be specified in such a manner that it is a function only of the steel yield strength at a test temperature which in turn is a function of the plate thickness and design temperature. The main reason for increasing the CVN energy requirement with increasing yield strength is to obtain a CVN energy level on the Charpy transition curve that is well above the lower shelf.

The lateral expansion requirement is recommended since this parameter serves as an additional guarantee that the CVN energy obtained is indeed measured well above the lower shelf of the Charpy transition curve. The lateral expansion is easily obtained from the CVN test.

The proposed requirements correspond to the as-welded (AW) condition and are based on "degradation" of the material in the HAZ corresponding to the widely accepted practice of maintaining the heat input in the range of 1.5 and 4.5 kJ/mm.

Based on experience with wide plate tests in the United Kingdom, the use of plates in AW condition is limited by thickness and design temperature considerations. Should the conditions stipulated in the requirements not be satisfied, one option is to stress relieve (PWHT) the welded joint. The base plates may then be qualified through Charpy testing and it will be noted that the requirements are relaxed compared to the as-welded condition for the same wall thickness. The above approach could be approved provided PWHT can be reliably monitored. Another approach is to evaluate the acceptability of the welded connection by means of fracture mechanics analysis.

Although the welding procedure qualification (WPQ) is outside the scope of the requirements discussed in this CSA group, it is strongly recommended to base WPQ on fracture toughness tests (e.g. COD) rather than on CVN tests for weldments involving large wall thicknesses. In the case that the heat input will exceed 4.5 kJ/mm it is emphasized that compliance with the proposed requirements needs to be properly documented also for the HAZ.

The proposed requirements are designed to comply with a maximum allowable utilization of the material (0.6 σ y) and requirements to elements with a lower degree of utilization may have to be considered separately.

2.2 DEFINITIONS

Design Temperature

T_D Air: Lowest monthly mean temperature (i.e., the minimum of the MMDMT curve, see Section 3 and Fig. 15) minus 5 degrees C.

The value of T_D Air is to be used for all elements above the Lowest Astronomical Tide (LAT).

Data sample of temperature observations representative of the temperature regime should be used.

T_D Sea: Design temperature for sea water, which should be taken as - 2 degrees C.

Structural Class/Application Categories

I_A/Special: Elements with at least one of the following characteristics:

- essential to the integrity and safety of the structure.
- low or no redundancy.
- designed to retain their fracture resistance throughout the life of the structure with little or no inspection.
- subject to particularly arduous stress conditions and/or high stresses in the plate thickness direction.

I_B/Primary: Elements with at least one of the following characteristics:

- Elements for which failure would endanger the structural integrity.
- Elements with low to intermediate redundancy which are accessible for inspection.
- Elements subject to stresses mainly in the plane of the plate.

II/Secondary: Elements other than those identified under classes I A and I B above.

Wall thickness

t: - Wall thickness (in mm) of base plate. In the case of different thicknesses of members meeting at a joint, reference thickness (in mm) should be used, see Fig. 5.

2.3 TOUGHNESS REQUIREMENTS

The proposed CVN toughnesses requirements are presented in Figs. 1 to 4. Figs. 1 and 2 show the test temperature as a function of thickness for plates in AW condition for primary (I A, I B) and secondary (II) structural categories respectively. Fig.3 shows the CVN energy requirements as a function of the steel yield strength. Impact properties are to be tested in compliance with CAN3-G40.20-M81.

2.4 APPLICATION OF CSA STRUCTURAL STEELS

The CSA Standard CAN 3 - G40.21 for Structural Quality Steels refers to six grades of steels with specified CVN energy requirements within the yield strength range discussed. These steels are identified in Table 1, and the five categories of CVN test temperatures specified in the CSA standard are shown in Table 2.

The CVN energy requirements recommended in the present document exceed those specified by the CSA Standard, see Fig. 3. Fig. 6 shows a comparison of CVN energy requirements specified by CSA (20 J) and those recommended, for three selected C-Mn microalloyed steels. The chemical composition and mechanical properties of these steels are given in Tables 3 and 4. This example shows that the recommended CVN energy requirements properly reflect the changes in the lower shelf energy level when increasing the yield strength. It is seen that the existing CSA requirements have been extended with regard to medium to high strength steels.

To demonstrate application of CSA steels for fixed offshore structures, the "equivalent" test temperatures for the CVN energy levels corresponding to the proposed requirements shown in Fig. 3, were obtained from the CVN reference curves in Fig. 22*. Figs. 7 to 14 show the applicability of individual CSA steels in the AW condition.

3. DESIGN TEMPERATURE

As suggested in the First Report, it is recommended that the design temperature be defined on a statistical basis. Assuming a large sample of temperature data (e.g., 30 years), the statistical parameters calculated represent well the entire temperature regime. The extreme temperature (e.g., the minimum temperature ever measured) is an arbitrary value and should not serve as a basis for the definition of the design temperature. Such terms as "mean daily", "mean monthly", etc., may also be found confusing without proper definition. Consequently, the definition of those statistical temperature parameters most commonly encountered are also included.

The word mean is used in the statistical sense and it represents the expectation of the random quantity (temperature).

Generally, there are two recorded temperatures every day:

DHT = Daily High (maximum) Temperature
DLT = Daily Low (minimum) Temperature

The calculated daily temperature parameter is the

DMT = Daily Mean Temperature

The means of DHT, DLT and DMT calculated for a sample of years define a set of new statistical parameters (MDHT, MDLT and MDMT) as shown in Fig. 15 Taking further monthly mean of MDHT, MDLT and MDMT the MMDHT, MMDLT and MMDMT are obtained.

The design temperature is a reference temperature used as a parameter for determining the required CVN test temperature. The minimum of the MMDMT curve (for the 12 months of the year) minus 5 degrees C is the recommended definition of the design air-temperature to be used in the chart of the proposed toughness requirements (Figs. 1, 2, and 4). This is normally also taken as corresponding to the lowest point on the annual "Mean Daily Low Temperature" (MDLT) curve.

The recommended design temperature for sea water is -2 degrees C.

Different approaches have been used in defining the design temperature and Table 5 identifies the definitions used by the relevant reference codes/standards.

The various definitions of the design temperature complicates a comparison of the toughness requirements in the different codes/standards.

In the following, two offshore scenarios (Grand Banks and North Sea) are considered and the design temperatures and the CVN test temperatures derived from the ABS (American Bureau of Shipping), DEn (Department of Energy, U.K.) and NPD (Norwegian Petroleum Directorate) are compared. The temperature data for Grand Banks were taken from (1).

Temperature records for:		Lowest MDMT	Lowest MMDMT	Lowest recorded
Grand Banks	a)	-4.9° C	-4.9° C	Not available
U.K. Waters	b)	Not available	+4.5° C	-10° C

Design Temperatures:		a)	b)
	ABS:	-4.9° C	—
	DEn:	—	-10° C
	NPD:	-9.9° C	-0.5° C
	Proposed:	-9.9° C	-0.5° C
Steel properties:		Yield 340-355 MPa	
Element catetory:		I A	
Stress Level:		Maximum allowable	
Wall thickness:		37.5 mm, 25 mm and 12.5 mm	
Test temperatures:		See Fig. 16	

The Fig. 16 shows graphically comparison of the test temperatures for different thicknesses and it is observed that wide variations exist.

The example assumed a yield strength for which the energy level for Charpy testing would be compatible (i.e., 34J). For different yield strength the energy requirement may also vary and thereby further complicate comparison of codes/standards.

4. TOUGHNESS VERSUS STRUCTURAL APPLICATION

The probability and consequences of unstable fracture for the various structural members and joints in an offshore installations vary considerably. In the process of design, so as to optimize steel use, different categories apply to structural members for the selection of the required material toughness level. The grouping into categories is based upon the following considerations:

- redundancy of the structural member;
- consequences of failure;
- stress level and type of applied stress;
- stress concentration;
- loading rate;
- type of loading (static, cyclic);
- experience with related structures; and
- accessibility for inspection and repair.

Usually, three structural categories are defined as special, primary and secondary, see Table 6.

Structural redundancy is an important factor. The degree of redundancy can be determined through various analysis, ranging from a full overall consequence analysis of the structure to a much more simplified approach. An example of the latter is given for the case of tensile loading, see Table 7. Table 8, (Ref. 2), shows some typical degrees of redundancy for different offshore installations.

5. EFFECT OF THICKNESS ON CVN TEST TEMPERATURE

In the recommended toughness requirements, the CVN test temperature (T_{test}) is a function of the design temperature (T_{des}) and the plate thickness (t), Fig. 1, so that

$$T_{test} = f(T_{des}, t) \qquad (1)$$

In the proposed requirements, the sensitivity of T_{test} to a unit change in T_{des} is equal to unity, i.e.,

$$\left[\frac{\partial f}{\partial T_{des}}\right]_{t = const} = 1 \qquad (2)$$

In other words, every drop in the design temperature must be compensated by the same drop in the test temperature.

The sensitivity of T_{test} to thickness is defined by the partial derivative,

$$\left[\frac{\partial f}{\partial t}\right]_{T_{des}} = \text{const} \qquad (3)$$

The thickness sensitivity thus reflects the penalty imposed on CVN test temperature (decrease in T_{test}) for every mm of increased thickness while keeping T_{des} constant. Taking into account the requirement that the design temperature sensitivity is equal to 1, equation (2), it is seen that the thickness sensitivity determines how much increase of the design temperature is necessary to compensate for 1 mm increase in plate thickness at constant test temperature.

As mentioned in the first Report, the recommended IACS formula for CVN test temperature, $T_{test} = f(T_{des}, t)$ is (3):

$$T_{test} = T_{des} - t + 30 \qquad (4)$$

From this formula, the design temperature sensitivity is

$$\left[\partial T_{test}/\partial T_{des}\right]_{t = \text{const}} = 1$$

and the thickness sensitivity is

$$\left[\partial T_{test}/\partial t\right]_{T_{des} = \text{const}} = -1^{\circ}\,C/mm$$

and it is independent of thickness.

The constant thickness sensitivity implied by Equation (4) can be applied in a narrow range of thicknesses, provided it is on the conservative side. However, a better approach is to make the thickness sensitivity dependent on thickness, Fig. 17, so that with increasing thickness, the sensitivity decreases. It should be noted that the thickness sensitivity reaches a constant value when approaching the plane-strain

threshold of fracture toughness, Figs. 18 and 19. It can be seen that when the relative change in thickness is taken into account (multiplying the thickness sensitivity by thickness), the resultant relative sensitivity is approximately constant, Fig. 20.

Similar thickness sensitivity trend can be observed in Fig. 21 (Ref. 2). The diagram relates to the welded wide plate data obtained by the British Welding Institute replotted by Lloyds Register for structural ship steel grades.

The thickness sensitivity in the present chart, Fig. 1, was kept the same as in Fig. 1* and 2*.

6. EFFECT OF PWHT ON CVN TEST TEMPERATURE

Post weld heat treatment of weldments in structural steels is beneficial since it reduces the tendency to brittle fracture in that it improves the toughness of the majority of commonly used weldments and the HAZ and reduces the level of tensile residual stresses. The latter will reduce the risk of brittle fracture by lowering the effective stress acting on defects in weld regions. At the same time it should be emphasized that there is evidence to indicate that the toughness in the HAZ may be reduced in certain microalloyed steels which show significant precipitation hardening in the HAZ following PWHT.

Through the literature survey performed, it was found that the U.K. Standards and Governing Regulations are the most comprehensive in regard to the specific requirements for PWHT. As a result of work carried out under the United Kingdom Offshore Research Programme on the fracture toughness of weldments typical of those used in offshore structures, PWHT is recommended in the following cases:

(i) For all nodal regions (stub-to-can connections and welds within the can) where the thickness of the plate being joined by the weld under consideration exceeds 40 mm (see Fig. 22 for definitions). PWHT of welds joining plates with thicknesses greater than 40 mm may be omitted if satisfactory performance in the as-welded condition can be demonstrated

by fracture mechanics tests on weldments, i.e., weld metals and HAZs taken from procedure test plates.

(ii) For areas away from nodes, including stub-to-brace closure welds, longitudinal seams in tubes, and tube to tube connections when the thickness involved exceeds 50 mm. For such joints PWHT may also be omitted on similar grounds to those given in (i) above.

The position is that the designer may chose to carry out PWHT and use conventional CVN testing or demonstrate through fracture mechanics tests and analysis, that the welded joints have adequate toughness to avoid brittle fracture. The tests are to be carried out on both the weld metal and material from the HAZ.

It has always been the practice in the pressure vessel industry to require PWHT for thicknesses above 40 mm. In many ways, the large intersections in offshore structures resemble those in pressure vessels and where they differ, it seems that conditions for offshore structures are more demainding (for example, no preload test, severe fatigue loading, continuous operation at low temperature). However, the through thickness stress gradient is beneficial in making the cracks less prone to propagate. This should be taken into account and only the relevant stresses in the vicinity of the defect should be considered (e.g., PD 6493). Introduction of PWHT in the fabrication process will increase costs but this increase is to a large extent governed by the fabrication process chosen. In "bent" construction the four sides of a jacket structure are built on the ground and the structure is completed by lifting the sides into position for final welding. In "node" construction, the intersections are built as subassemblies with brace stubs being welded to stiffened or thickened leg cans. The nodes are PWHT and then erected into the platform by welding the main legs and braces to the appropriate stubs with closure welds. These welds are both thinner than the node welds and remote from the stress consentration factor region and will usually not be subjected to PWHT. The control of the PWHT process is consequently better for "node" construction.

VERITAS has collected results from a large number of fracture mechanics tests related to design, fabrication and inspection of platforms, pipelines, pressure vessels and piping systems. Both base material and weldments were tested by various standardized fracture mechanics laboratory tests. The majority of tests were performed on joints fabricated by manual metal arc welds (MMAW) or submerged arc welds (SAW). In Table 9 the lower bound values for minimum single COD-values measured at maximum loads are shown. The results shown in the table represent a population of approximately 460 weld metals and 230 HAZ COD-test specimens. The base materials were C-Mn normal or high strength structural steels, fine grain treated and normalized with impact toughness specified at -40 to -50 degrees C. The welding was typical for offshore welding procedures, i.e., max. 3-4 kJ/mm.

The results show that the HAZ is normally of high toughness and that the weld metal is the region of lowest toughness, particularly in the AW condition.

Generally, the weld metal toughness increases appreciably after PWHT although some weld metals corresponding to the greater thickness are still of rather low toughness. According to the results it would appear that it would not be necessary to perform PWHT to obtain acceptable HAZ toughness. It is, however, also important to consider failure modes other than brittle fracture. Delayed cracking may occur in thick weldments, and may cause defect initiation. Even at high toughness, it may be justified to do PWHT and it is interesting to notice that the International Institute of Welding has generally recommended PWHT for welded joints (C-Mn steel) for thicknesses in excess of 50 mm, which is the limit often specified for offshore structures. The U.K. toughness requirements for selection of materials at service temperatures below 0 degrees C are based on the results of a number of notched and welded Wells Wide Plate Tests for C and C-Mn steel plates, carried out at the U.K. Welding Institute.

The requirements proposed in the present document for the base materials to be used in a PWHT joints are defined in Fig. 4. It can be seen that these are in good agreement with the requirements specified in BS 6235 (1982) when considering the effect of different definitions of the design temperature .

In Fig. 23 the wall thicknesses and corresponding test temperatures from BS 6235 for Grade 43 and 50 steels in the AW condition are plotted. By assuming these values to be applicable to the I A elements, as we interpret BS 6235, a spread in the corresponding proposed design temperatures is found. Due to the BS requirement of 27 Joule for Grade 50 (yield strength 325-355 MPa) the values plotted on the design temperature scale should be increased by approximately 5 degrees C to correspond with proposed energy requirements. The spread will then lie between - 5 and 0 degrees C and thereby indicate the difference (here, approximately 5 degrees C) between the proposed design temperature and the one used by DEn (i.e., T_D approximately - 6 to - 10 degrees C) for the same location. Similarly, an offset of approximately 5 degrees C can be found when comparing the BS 6235 toughness requirements in the PWHT condition with the proposed requirements of Fig. 4.

The suggested limitation for a reference thickness of 25 mm in the AW condition at a design temperature of -30°C is based on an estimate derived from fracture mechanics analysis (First Report, Section 6.3.)

7. FRACTURE MECHANICS CONSIDERATIONS

Safety against unstable fracture is just one step towards overall structural integrity assurance. Fracture toughness of steel for Canadian offshore and Arctic applications is clearly an important consideration. Ice loading in impact situations and the thick steel plates necessitated by high local ice pressure and low temperatures, demand exceptional toughness. Structural redundancy, crack arrestors, inspection provisions, proper joint and detail design, as well as inherent fracture resistance, contribute to the structural integrity.

The toughness requirements represented by Figs. 1 to 4 are based on service experience with structures related to the CVN transition curve, Fig. 24. This experience is limited to moderate plate thicknesses and to moderately low service (design) temperatures.

Within its limitations, the CVN toughness approach provides, together with a good design practice, pre-service and in-service inspection, acceptable safety against unstable fracture. The CVN toughness requirements for the base plate in AW condition should guarantee enough fracture resistance to prevent unstable crack propagation through the plate from pop-ins of small defects (usually cracks) from locally embrittled zones.

However, there are cases for which fracture control by means of CVN testing is not adequate, and the option for full fracture mechanics assessment must be provided in the code. Critical structural elements (special areas) must possess enough fracture resistance to prevent unstable fracture during the whole service life of the structure from initial or fatigue propagated defects.

Unstable fracture events may consist of a linear elastic brittle fracture, elastic plastic deformation prior to brittle fracture, or a fully plastic ductile fracture. The following main factors affect the risk of unstable fracture:

- Stress level (cyclic and maximum);
- Fracture toughness; design temperature and loading rate;
- Defect size (initial and size of propagating defect);
- Local geometry in the vicinity of defect (stress concentration factor, thickness, constraint).

In cases where this is justified, the fracture control criteria and associated fracture mechanics testing of the weldment will ultimately decide acceptability of the base plate for the welded joint. Tables 10 and 11 (Ref. 2), show examples of cases when fracture mechanics strength assessment at the design stage may become necessary.

The main emphasis is put on design against initiation of unstable fracture; however, a crack arrest design philosophy may also be considered when appropriate. The latter should be performed in the light of the crack arrest design philosophy applied in the aviation industry using the design of stiffened panels. Strength of the membrane and stiffener is optimized so that a propagating crack in the skin would arrest in the

vicinity of the nearest stiffener. This is achieved by a redistribution of loads into the stiffener acting as an effective mechanical arrestor. Similar design philosophy could be applied in certain areas of stiffened offshore structures.

8. EFFECT OF STRESS LEVEL ON TOUGHNESS REQUIREMENTS

When fracture mechanics assessments are incorporated in the design stage, the utilization of the material may be performed either through derivation of the maximum allowable stress or through minimum fracture toughness requirements.

In the LEFM range, using the limit state design, the maximum allowable nominal stress level should be derived from the following expression:

$$\sigma_{nom\,max} \leq \frac{1}{\gamma_m} \frac{K_c}{g(a, B, a/2c, M_x, M_b)\sqrt{\pi a}} \qquad (5)$$

Where

K_c = the fracture toughness

γ_m = material coefficient

2a = crack length

g = geometry factor

The values of fracture toughness, K_c, should be documented, based on the actual material chosen. The crack size, a, is here the maximum predicted crack size to occur during the operating life or prescribed inspection period, either the maximum size of undetected preexisting defect or the predicted fatigue crack through a proper fatigue crack growth analysis for dynamic loading.

The lowest value of σ_{max} derived from Equation (5) or from the corresponding conventional ULS strength criteria such as plastic overloading and buckling will govern the design. An optimal solution may be obtained when similar maximum stress levels are derived for all ULS criteria inciuded.

For elastic-plastic conditions (EPFM) the maximum allowable stress may be derived from the WI-COD design curve as follows:

$$\sigma_{nom\,MAX} \leq \frac{1}{\gamma_m} \left[\frac{COD \cdot \sigma_y \cdot E}{2\pi a\, g^2(a, B, a/2c, M_k, M_b)} \right]^{1/2} \cdot \frac{1}{SCF}$$

for $\sigma/\sigma_y \leq 0.5$

For $\sigma/\sigma_y \geq 0.5$

$$\sigma_{max} \leq \frac{1}{\gamma_m} \frac{\sigma_y}{SCF} \left[\frac{COD \cdot E/\sigma_y}{2\pi a\, g^2(a, B, a/2c, M_k, M_b)} + 0.25 - \frac{\sigma_{res}}{\sigma_y} \right] \qquad (6)$$

For tubular joints, SCF represents the geometric stress concentration factor at the hot spot with reference to the maximum stress allowed in the brace, while the local additional stress concentration due to the weld profile is reflected in M_k included in $g(\cdot)$. Also, a criterion based on the J-integral, may be applied similarly for the strength assessment.

When the ULS maximum stress is determined through the conventional strength criteria only, the minimum required fracture toughness level of the materials and welded connections is given by conversion of previous equations as:

$$K_{c\,min\,required} \geq \sigma_{max} \cdot g(a, B, a/2c, M_k, M_b) \sqrt{\pi \cdot a} \qquad (7)$$

in the LEFM region and similarly:

$$COD_{min} \geq \gamma_m^2 \cdot 2\pi a g^2 \frac{\sigma_y}{E} \times \left(\frac{\sigma_{max}}{\sigma_y} \right)^2, \quad \frac{\sigma}{\sigma_y} \leq 0.5 \qquad (8)$$

$$COD_{min} \geq \frac{2\pi a}{E}\sigma_y^2\left[\frac{SCF \cdot \sigma_{net}^{MAX}}{\sigma_y} + \frac{\sigma_{res}}{\sigma_y} - 0.25\right], \frac{\sigma}{\sigma_y} \geq 0.5 \qquad (9)$$

in the EPFM region.

If the predicted minimum required fracture toughness is not achievable for present structural materials, the maximum allowable stress should be modified and determined as given in the section above. Necessary local design modifications should then lead to achievement of an ultimate stress level below the derived maximum allowable stress level.

9. CONCLUSIONS

- This report addresses Steel Plate Requirements for Fixed Offshore Structures for operation off the East Coast of Canada. It documents a critical review of existing design codes and the relevant literature. The report also incorporates our response to the comments made by the CSA materials working Group on the first draft of the report.

- Design of offshore structures may be based on various structural design philosophies. These can be structural design based on safe-life, fail-safe, and damage-tolerance. In all cases, safety against unstable fracture is an important aspect of the overall safety considerations and include requirements to structural steels and weldments.

- The report addresses the fail-safe and damage-tolerant design methods by introducing the significance of elements for structural redundancy and suggesting fracture mechanics analysis where simple test methods and service experience do not provide the necessary and sufficient basis for decision-making.

- Fracture control plans should be established for all major offshore projects and may range from impact notch toughness testing as a screening criterion for the

selection of structural steels and weldments to complex fracture mechanics analysis.

- Years of service experience have established confidence in using CVN testing as a quality control tool for a certain range of plate thicknesses and service temperatures and this is reflected in the proposed requirements. Together with good design and fabrication practices, the proposed toughness requirements are believed to provide an acceptable safety against unstable fracture.

- Since both the base material and the weldment must possess sufficient toughness, the Welding Procedure Qualification becomes an extremely important part in the fracture control plan. For joints with large thicknesses, it is strongly recommended that these are qualified by means of fracture mechanics considerations and fracture toughness tests.

- The requirements for steel plates are linked to the method of fabrication and distinguish between the as-welded and stress relieved condition. The effect of stress relieving or post weld heat treatment (PWHT) in reducing the risk of fracture is generally accepted and it is reflected in relaxed toughness requirements. It is crucial to have every PWHT undergo a stringent quality control to ensure its effectiveness in improving toughness.

10. REFERENCES

1. "Canadian Sub-Arctic Temperature Parameters for Structural Steel Standards." Arctec Canada Ltd., Rep. 1841C-DR, submitted March 1984 to Canadian Coast Guard.

2. Lereim, J.; DnV Internal Communication.

3. Murer, C.; "Strengthening of Hull Structures in Ice." DnV Paper No. 83-P008.

TABLE 1 Relevant CSA G40.21 Steels

Grade *)	Minimum Yield Point	Minimum Average Impact Energy **)
260 WT	260 MPa	20 Joules
300 WT	300 MPa	20 Joules
350 WT	350 MPa	27 Joules
400 WT	400 MPa	27 Joules
350 WT	350 MPa	27 Joules
400 WT	400 MPa	27 Joules

WT = Weldable Notch Tough Steel

AT = Atmospheric Corrosion Resistant Weldable Notch Tough Steels.

*) All steels fully killed and fine grain practice applied.

**) Longitudinal specimens

TABLE 2 Standard Impact Test Temperatures
CSA G 40.21 Steels.

Category	Standard Test Temperature, degree C.
1	0
2	-20
3	-30
4	-45
5	To be specified by purchaser

TABLE 3

Chemical Composition Selected Steels

Steel	C	Mn	Si	P	S	Ni	Al	Cu	Cr	Mo	Sn	N
A	0.22	1.13	0.05	0.011	0.030	0.05	0.008	0.13	0.03	0.006	0.018	0.006
B	0.20	0.86	0.19	0.020	0.020	0.08	0.045	0.15	0.04	0.018	0.012	0.006
C	0.26	0.50	0.03	0.012	0.039	0.2	0.012	0.03	0.03	0.006	0.003	0.004

TABLE 4

Mechanical Properties Selected Steels

Steel	Yield Strength [MPa]	Ultimate Strength [MPa]	Elongation 2 in [%]	Elongation 8 in [%]	Reduction of area [%]	Hardness Rockwell
A*)	317	497	45	23	62	81
B	286	483	39	28	56	67
C	243	407	41	34	58	60

*) Quenched and 1% drawn.

TABLE 5 Design Temperature, Different Codes

	Above waterline	Below waterline
ABS	Lowest average daily atmospheric temperature	0 degrees C or higher pending supporting data.
API		
BS	In UK waters; suitable temperature for design purpose chosen as -10 degrees C south of the 54 degrees N	In UK waters; 0 degrees C.
DoE	and -6 degrees C north of that latitude.	
DnV	The lowest monthly mean temperature minus 5 degrees C.	The lowest monthly mean temperature minus 5 degrees C.
NPD	"	In Norwegian waters; 0 degrees C.

TABLE 6 Structural Application Categories

Application Category	Material Class	Element Characteristics
Special	IA	. Elements essential to the integrity and safety of the structure. Low or no redundancy. . Elements designed to retain their fracture resistance throughout the life of the structure with little or no inspection. . Elements subject to particularly arduous stress conditions and/or high stresses in the plate thickness direction.
Primary	IB	. Elements which failure endangers the structural integrity. Low to intermediate redundancy with access for inspection. . Elements subject to stresses mainly in the plate plane.
Secondary	II	. Elements other than those identified under class I above.

TABLE 7 Redundancy, Tensile Loading
Degree of redundancy for tensile loading, suggested definitions

Degree of redundancy	% Increase in nominal stress level of remaining structural load bearing elements caused by first local failure in one of the joined interacting elements.
High	$\Delta\sigma < 15\%$
Intermediate	$15\% \leq \Delta\sigma < 30\%$
Low	$30\% \leq \Delta\sigma < 100\%$
No	$100\% < \Delta\sigma$

TABLE 8 Degree of Redundancy, Typical Examples

Type of Object	Degree of Redundancy
Pipeline	No
Jacket Legs Substructure No of legs ≥ 8	Intermediate
Jacket Legs Substructure No of Legs < 8	Low
Deck Structure	Intermediate

TABLE 9 COD Test Results
Lowest Single COD's (mm) at max load for weld metals and HAZ (0 to -10°C)

Condition	Location	Thickness mm / Process	50-55	60	70	75	80	90	100
AW	WELD	MMAW	0.08	0.09	0.08	0.10	0.07	-	0.04
	HAZ		0.15	0.35	0.35	0.35	0.35	-	-
	WELD	SAW	0.18	0.11	0.06	0.20	0.23	0.11	-
	HAZ		0.35	0.18	>0.26	>0.26	-	-	-
PWHT	WELD	MMAW	0.10	0.26	0.26	-	>0.26	0.12	0.06
	HAZ		0.26	>0.26	>0.26	>0.26	>0.26	-	>0.26
	WELD	SAW	>0.26	>0.26	0.15	0.14	0.16	>0.26	>0.26
	HAZ		0.2	0.2	>0.26	-	-	-	0.24

TABLE 10 As-welded Condition
Inclusion of fracture mechanics strength assessment at design stage

	Plate Thickness (mm)	Importance of struct. detail	Degree of redundancy			
			High	Interm	Low	No.
Access for inspect and repair	< 25	Special	No	No	No	No
	25 ≤ t < 50	Primary	No	No	Yes	Yes
		Special	No	No	Yes	Yes
	50 ≤ t < 75	Primary	No	Yes	Yes	Yes
		Special	No	Yes	Yes	Yes
	75 < t	Primary	Yes	Yes	Yes	Yes
		Special	Yes	Yes	Yes	Yes
No access for inspect and repair	< 25	Primary	No	No	No	Yes
		Special	No	No	Yes	Yes
	25 ≤ t < 50	Primary	No	Yes	Yes	Yes
		Special	Yes	Yes	Yes	Yes
	50 ≤ t	Primary	Yes	Yes	Yes	Yes
		Special	Yes	Yes	Yes	Yes

TABLE 11 Stress relieved Condition (PWHT)
Inclusion of fracture mechanics strength assessments at design stage

	Plate Thickness (mm)	Importance of struct. detail	Degree of redundancy			
			High	Interm	Low	No
Access for inspect and repair	< 25	Special	No	No	No	No
	25 ≤ t < 50	Primary	No	No	No	Yes
		Special	No	No	Yes	Yes
	50 ≤ t < 75	Primary	No	No	Yes	Yes
		Special	No	Yes	Yes	Yes
	75 < t	Primary	No	Yes	Yes	Yes
		Special	Yes	Yes	Yes	Yes
No access for inspect and repair	< 25	Primary	No	No	No	No
		Special	No	No	No	Yes
	25 ≤ t < 50	Primary	No	No	Yes	Yes
		Special	No	Yes	Yes	Yes
	50 ≤ t	Primary	No	Yes	Yes	Yes
		Special	Yes	Yes	Yes	Yes

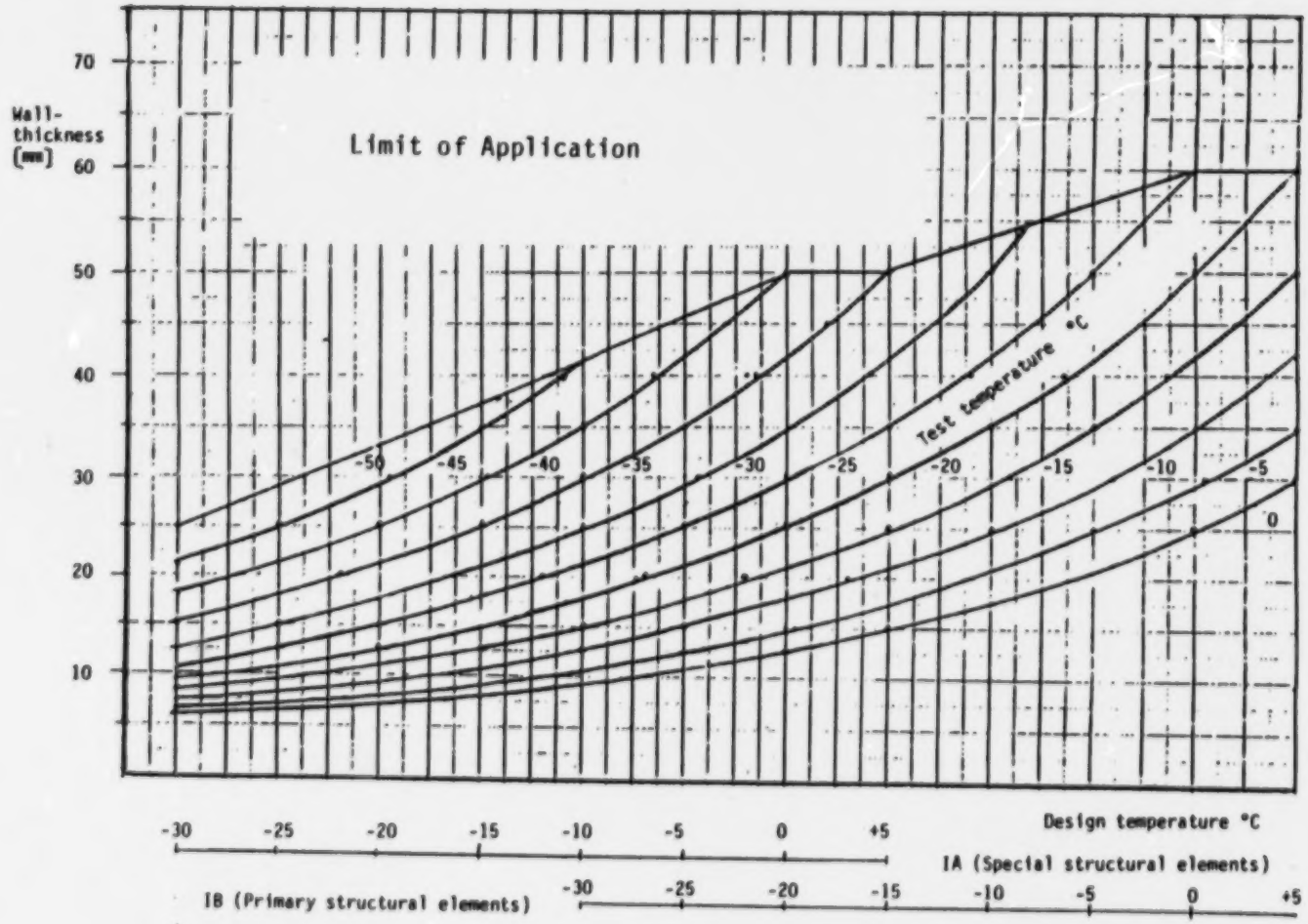


Figure 1: Toughness Testing Requirements for Class IA and IB Elements, As-welded.

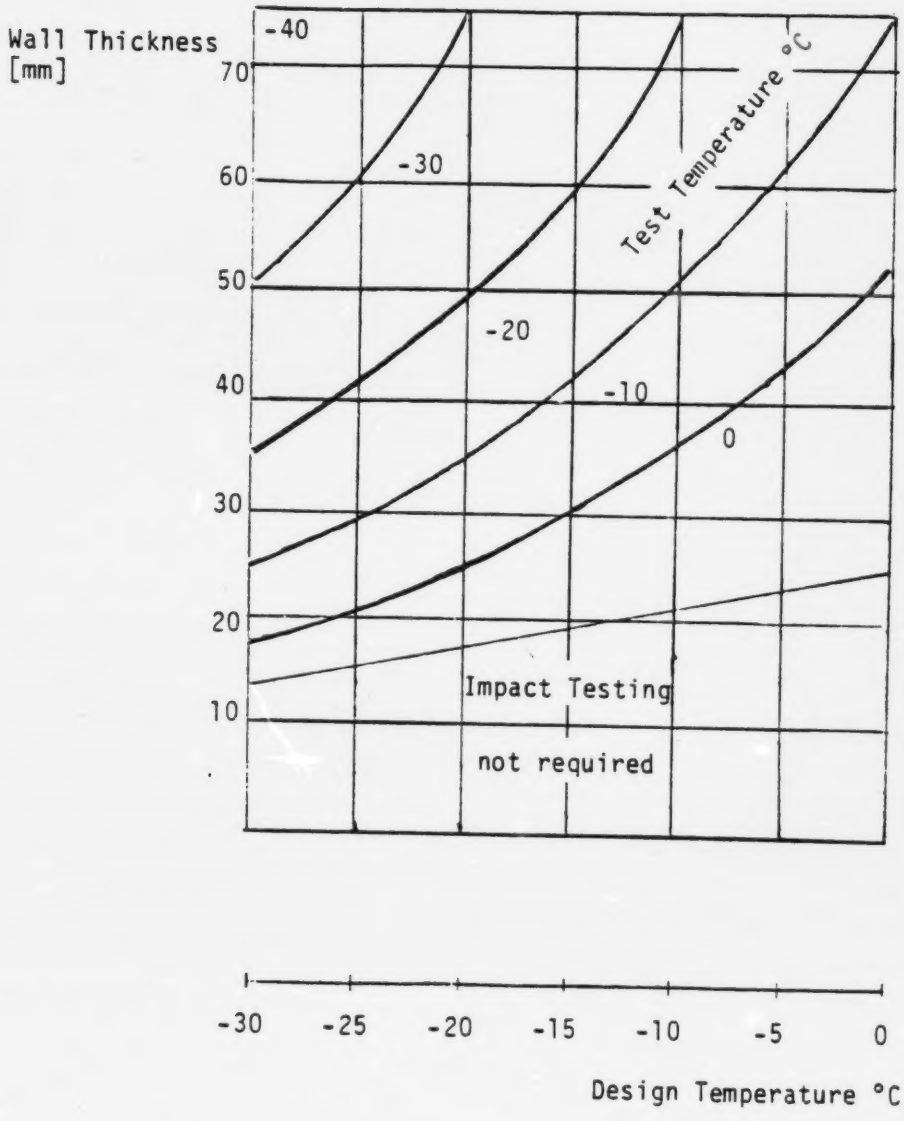


Figure 2: Toughness Testing Requirements for Class II Elements, As-welded.

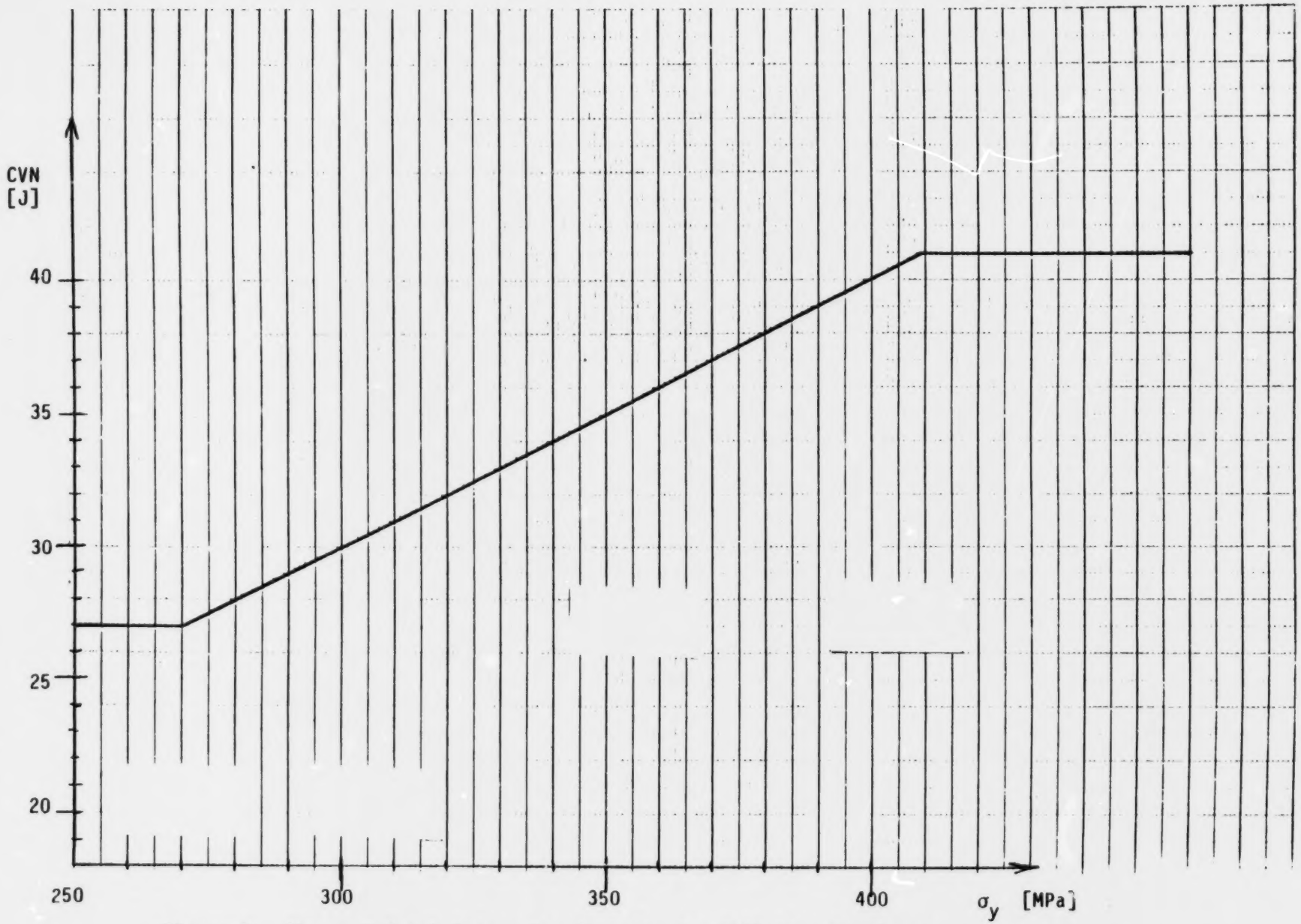


Figure 3: Charpy V-Notch Energy Requirements for Full-Size Specimens

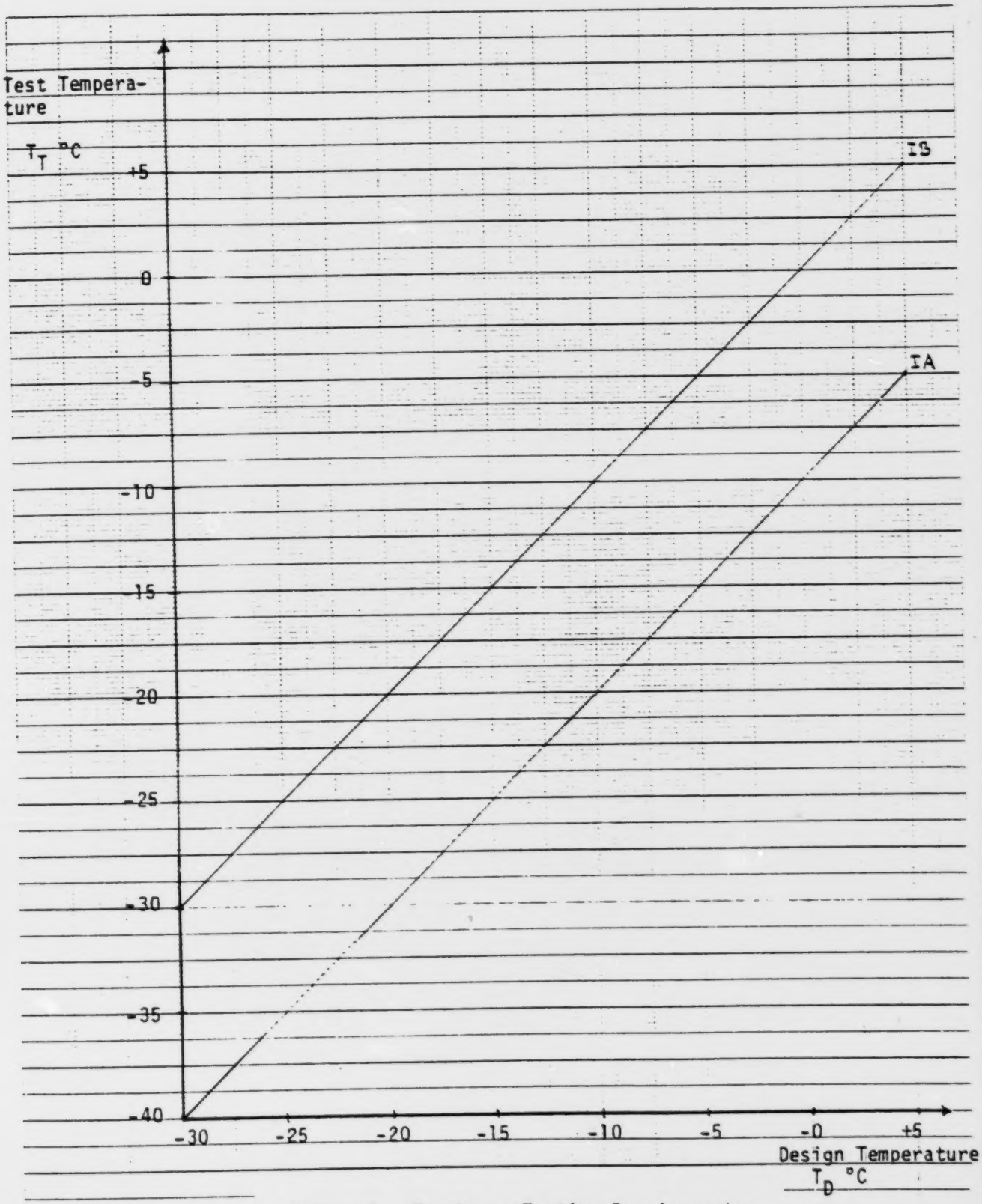
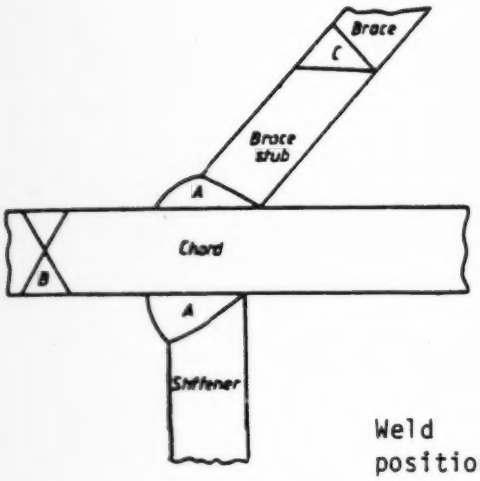


Figure 4: Toughness Testing Requirements for Class IA and IB Elements PWHT



Weld position	Reference thickness
A	Thickness of Brace Stub or Stiffener whichever is greater
B	Chord thickness
C	Brace thickness

Figure 5: Reference Thickness

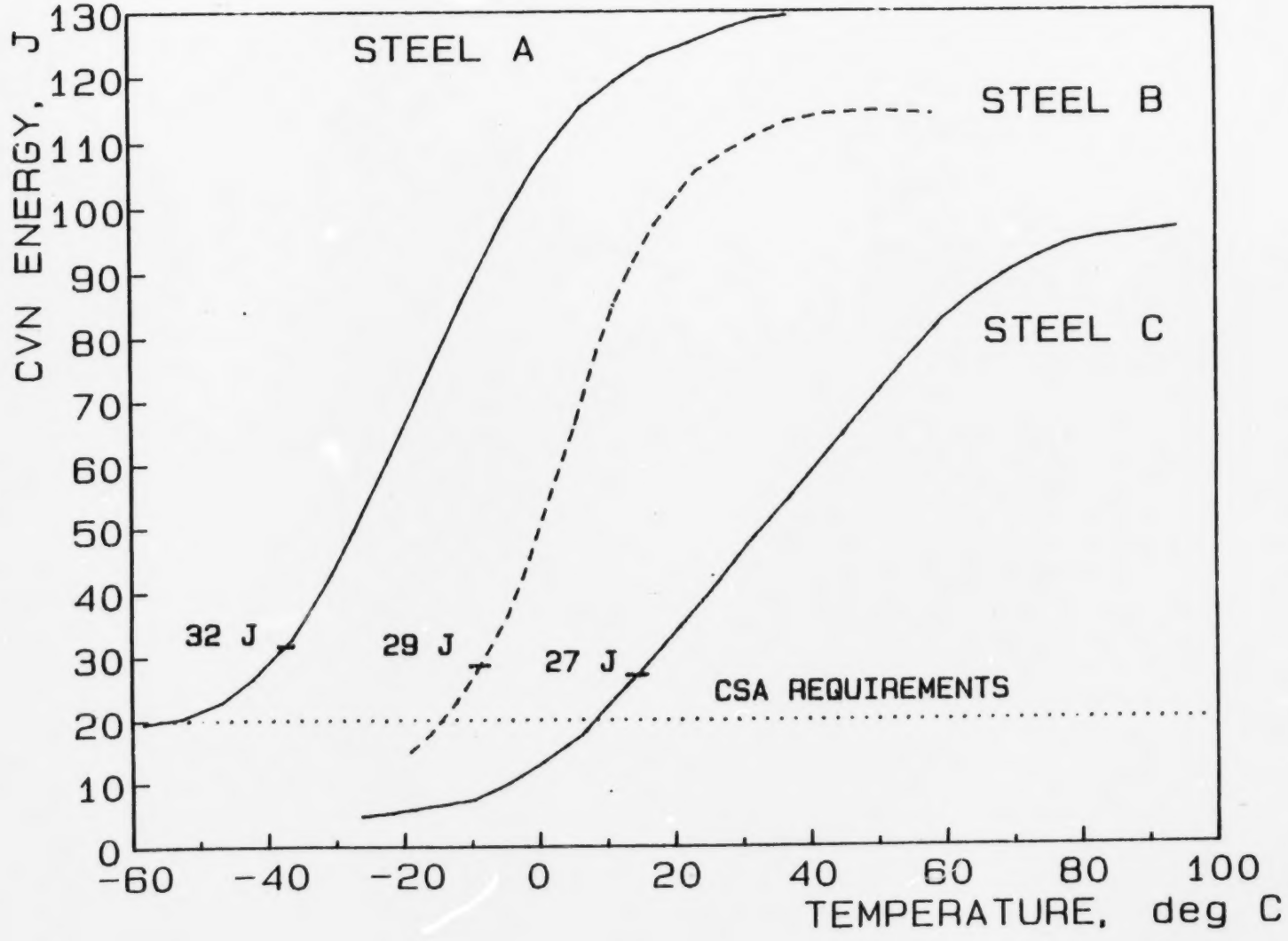


Figure 6: Transition Curves, Selected Steels

CSA G 40.21 M 81
Structural Quality
Steels

300 WT Category 2

As-welded condition shown.

The steel plate(s) will qualify for a thickness/ design temperature-combination found below or to the right of the "thick line".

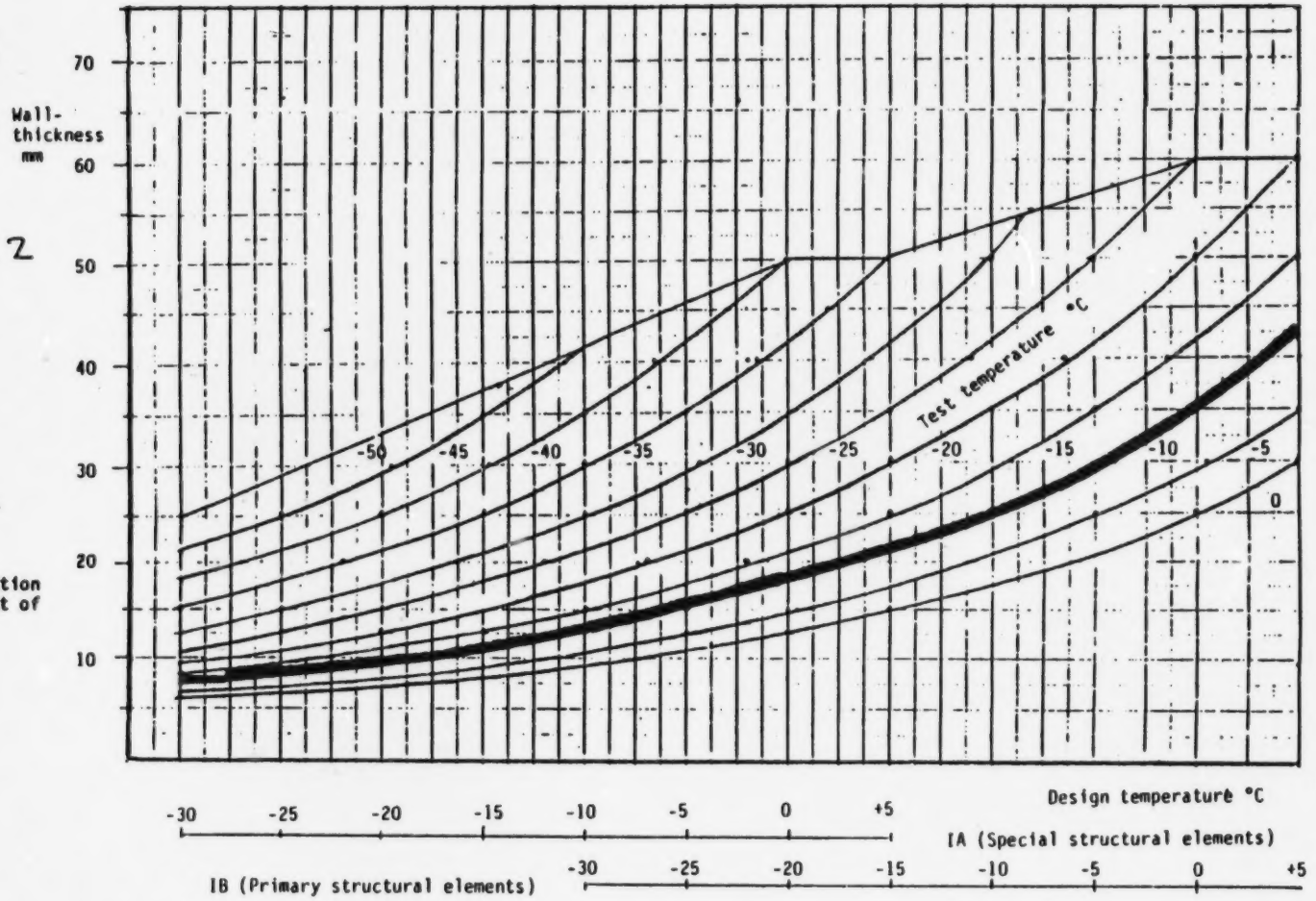


Fig. 7: Comparison with CSA Steel Grades

CSA G 40.21 M 81
Structural Quality
Steels

260 WT Category 2
350 WT " 2
350 AT " 2

As-welded condition shown.

The steel plate(s) will qualify for a thickness/ design temperature-combination found below or to the right of the "thick line".

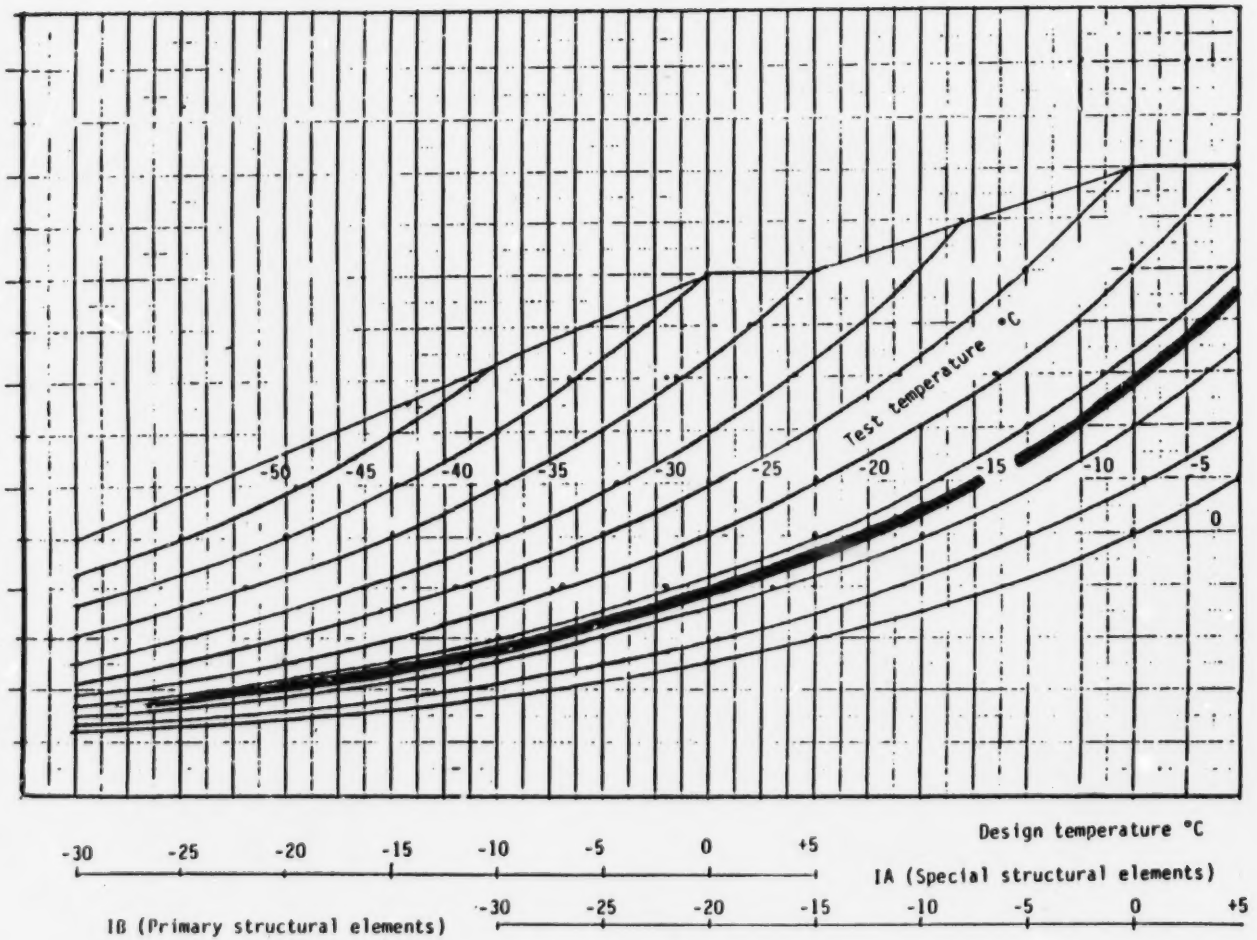


Fig. 8: Comparison with CSA Steel Grades

CSA G 40.21 M 81
Structural Quality
Steels

400 WT Category 2

As-welded condition shown.

The steel plate(s) will qualify for a thickness/ design temperature-combination found below or to the right of the "thick line".

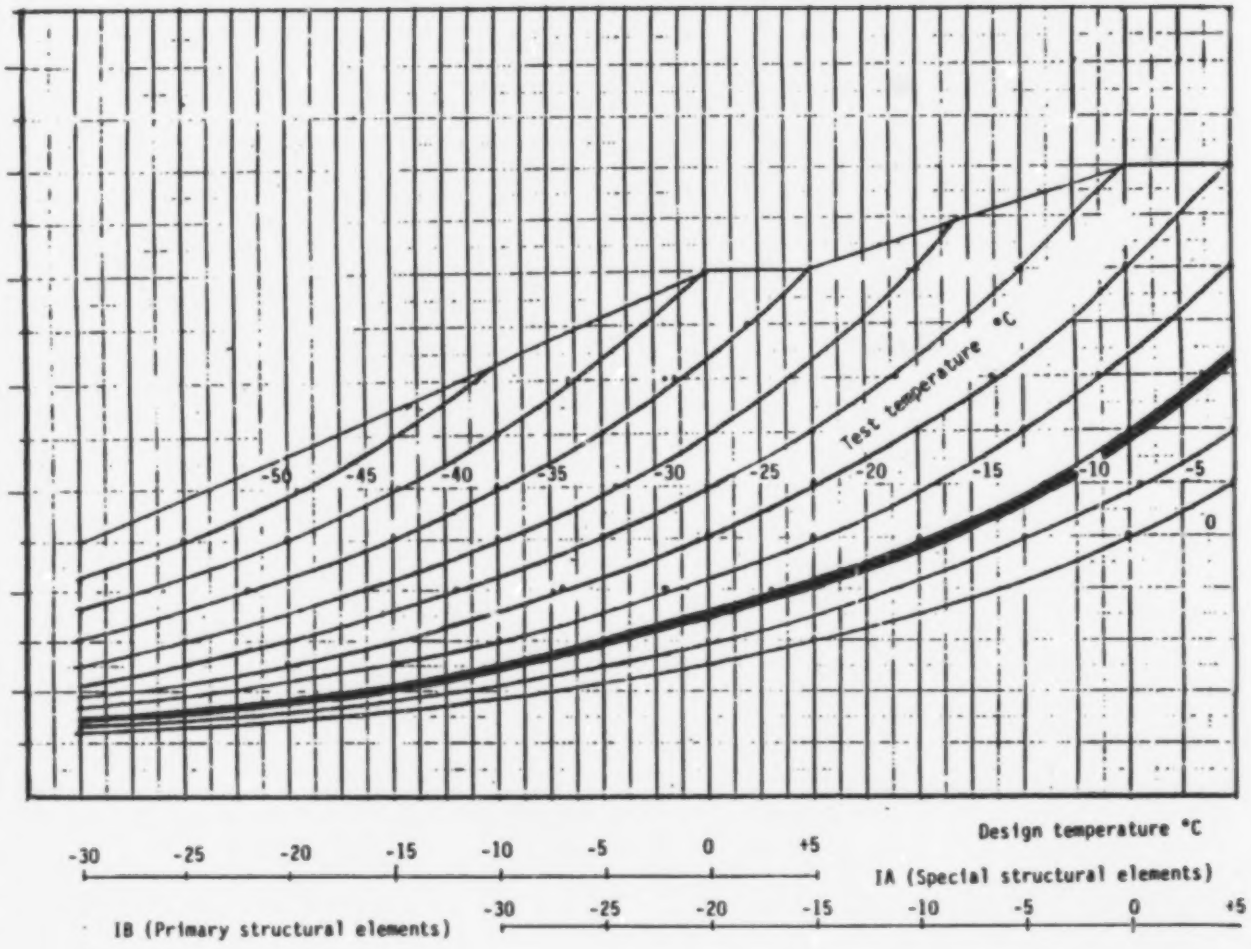


Fig. 9: Comparison with CSA Steel Grades

CSA G 40.21 M 81
Structural Quality
Steels

300 WT Category 3

400 WT " 3

As-welded condition shown.

The steel plate(s) will qualify for a thickness/ design temperature-combination found below or to the right of the "thick line".

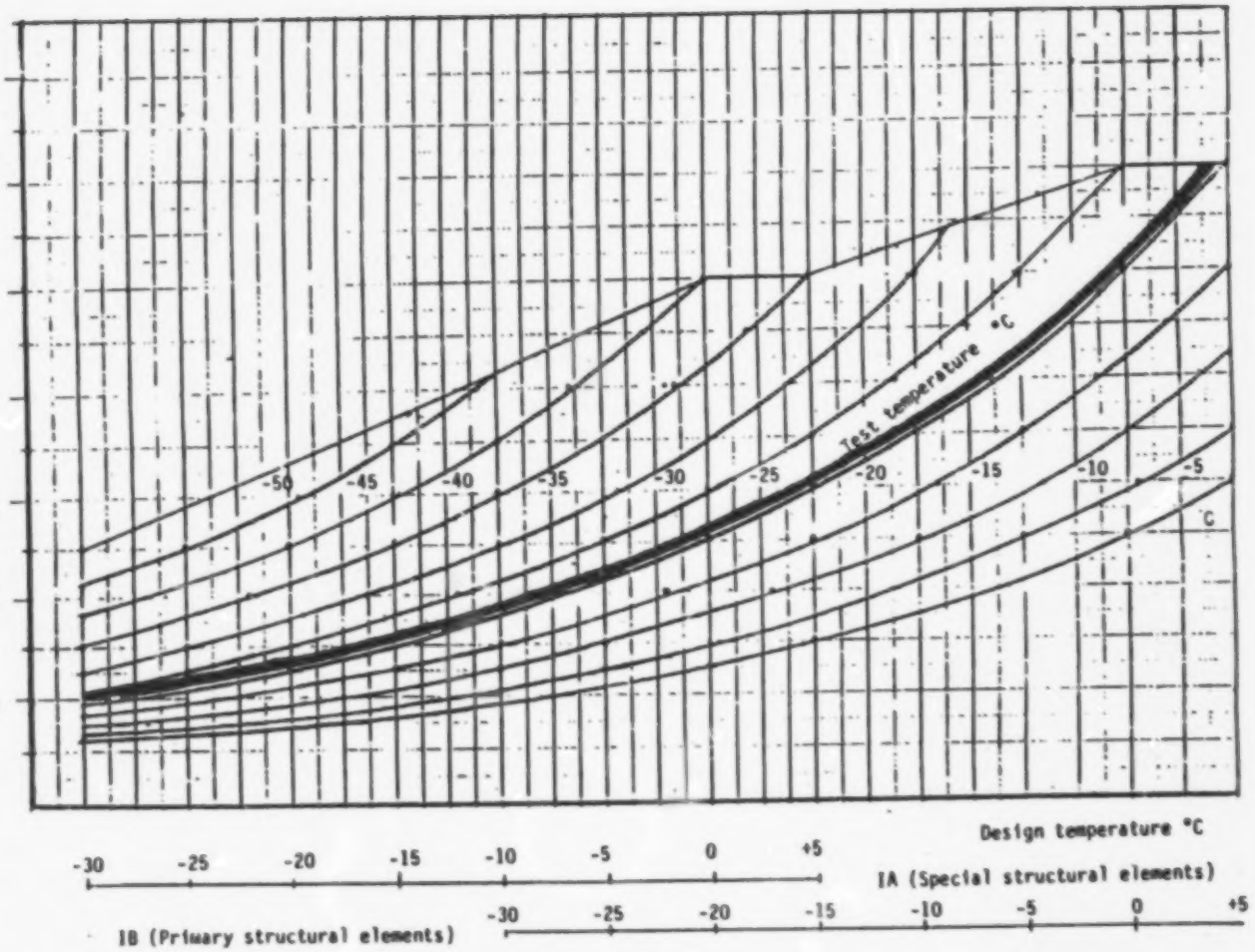


Fig. 10: Comparison with CSA Steel Grades

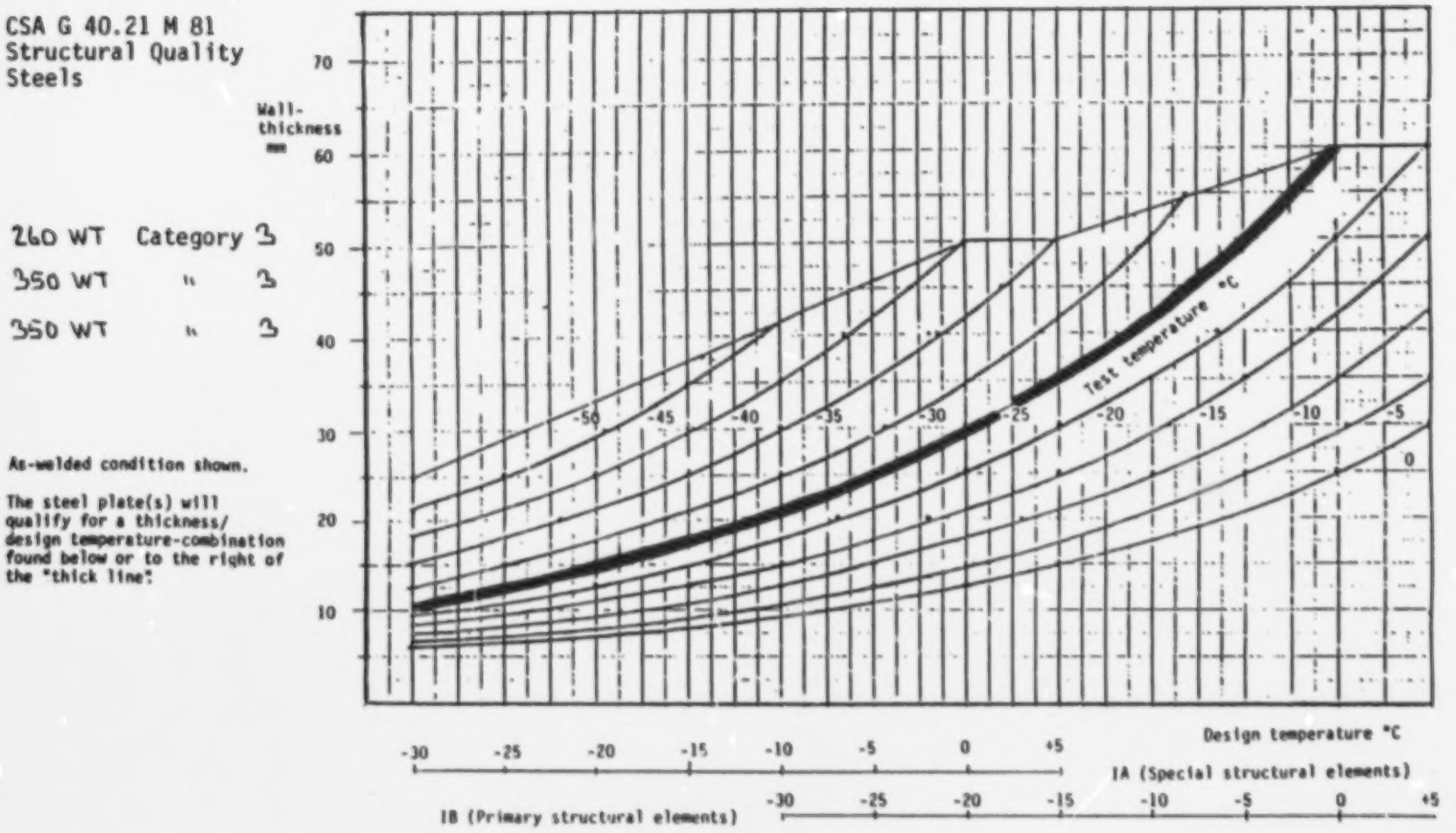


Fig. 11: Comparison with CSA Steel Grades

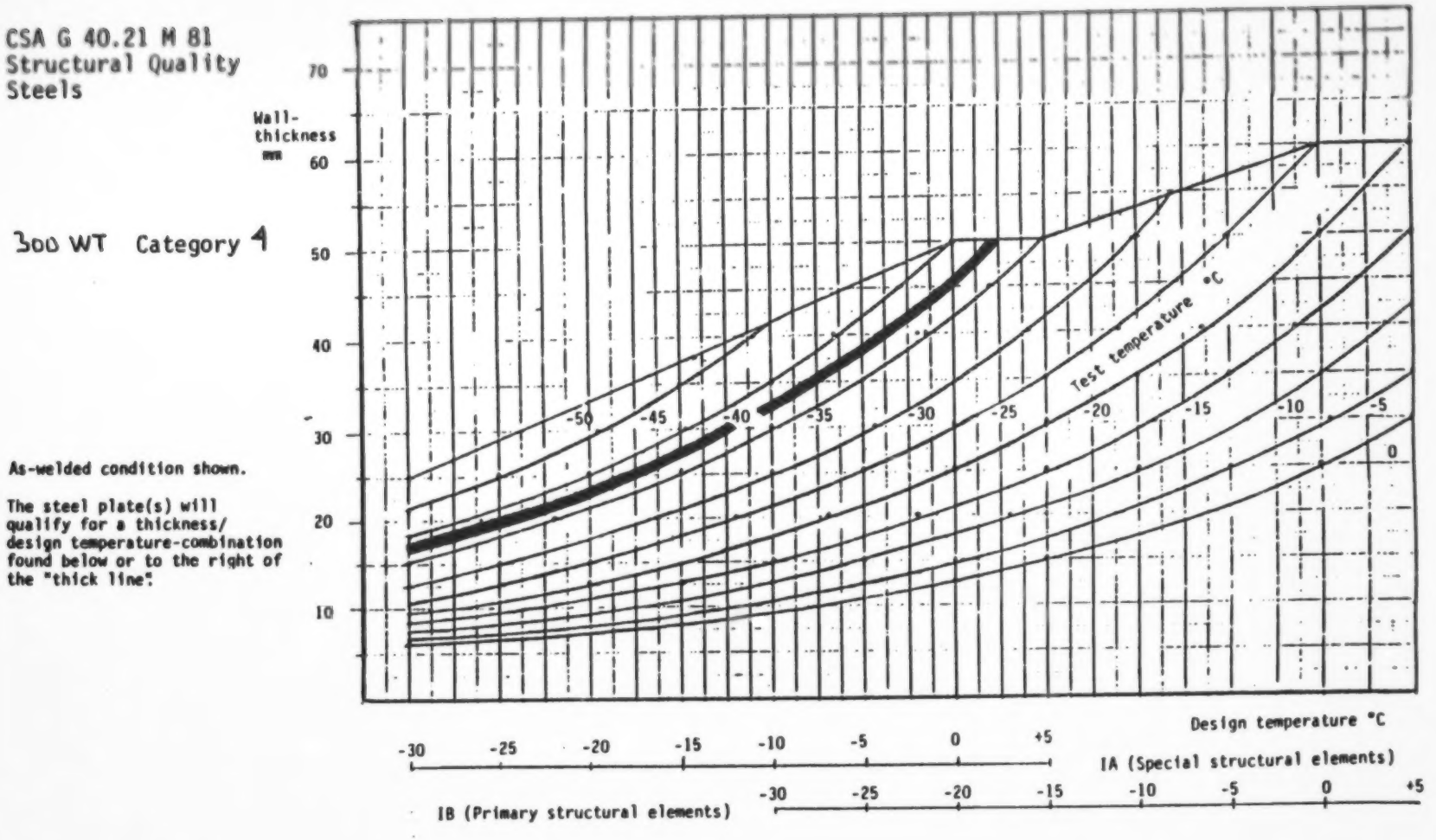


Fig. 12: Comparison with CSA Steel Grades

CSA G 40.21 M 81
Structural Quality
Steels

260 WT Category 4

350 WT " 4

350 AT " 4

As-welded condition shown.

The steel plate(s) will qualify for a thickness/ design temperature-combination found below or to the right of the "thick line".

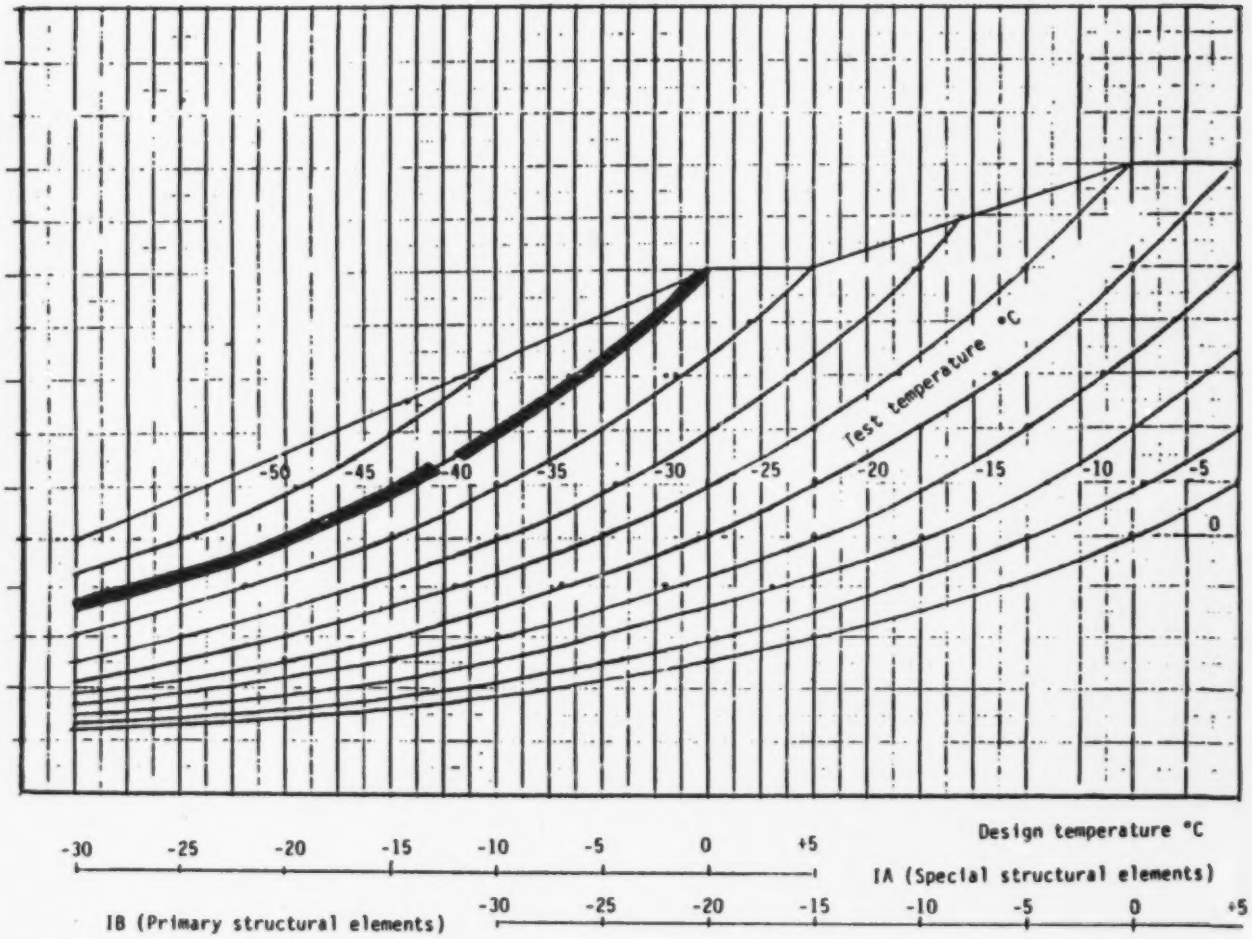


Fig. 13: Comparison with CSA Steel Grades

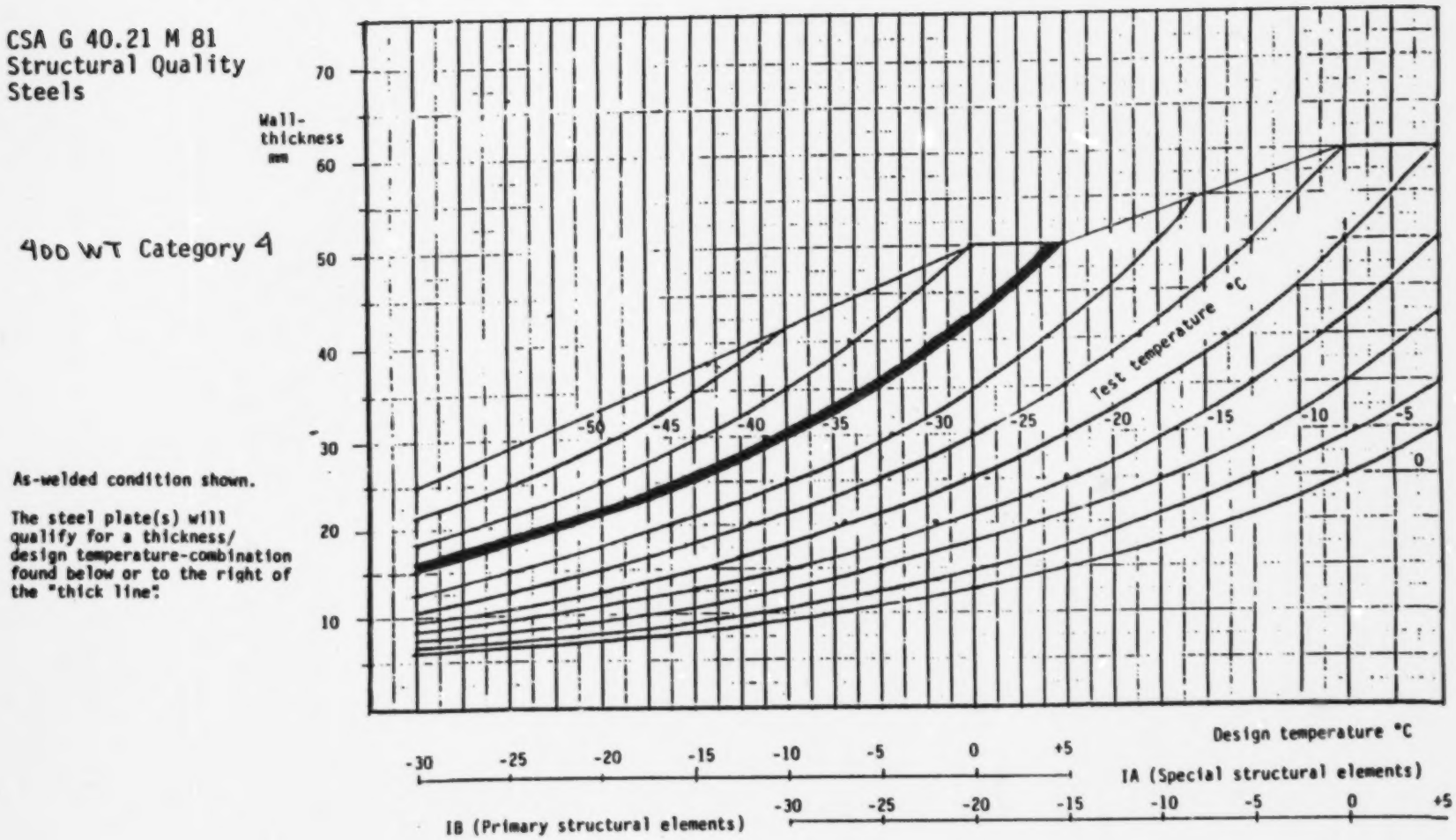
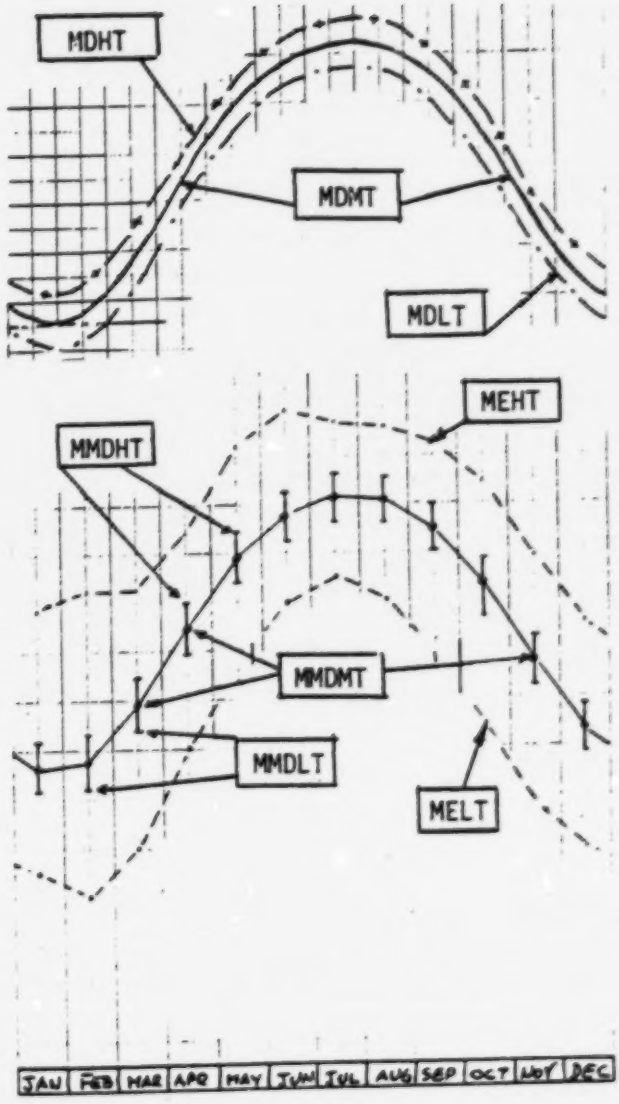


Fig. 14: Comparison with CSA Steel Grades



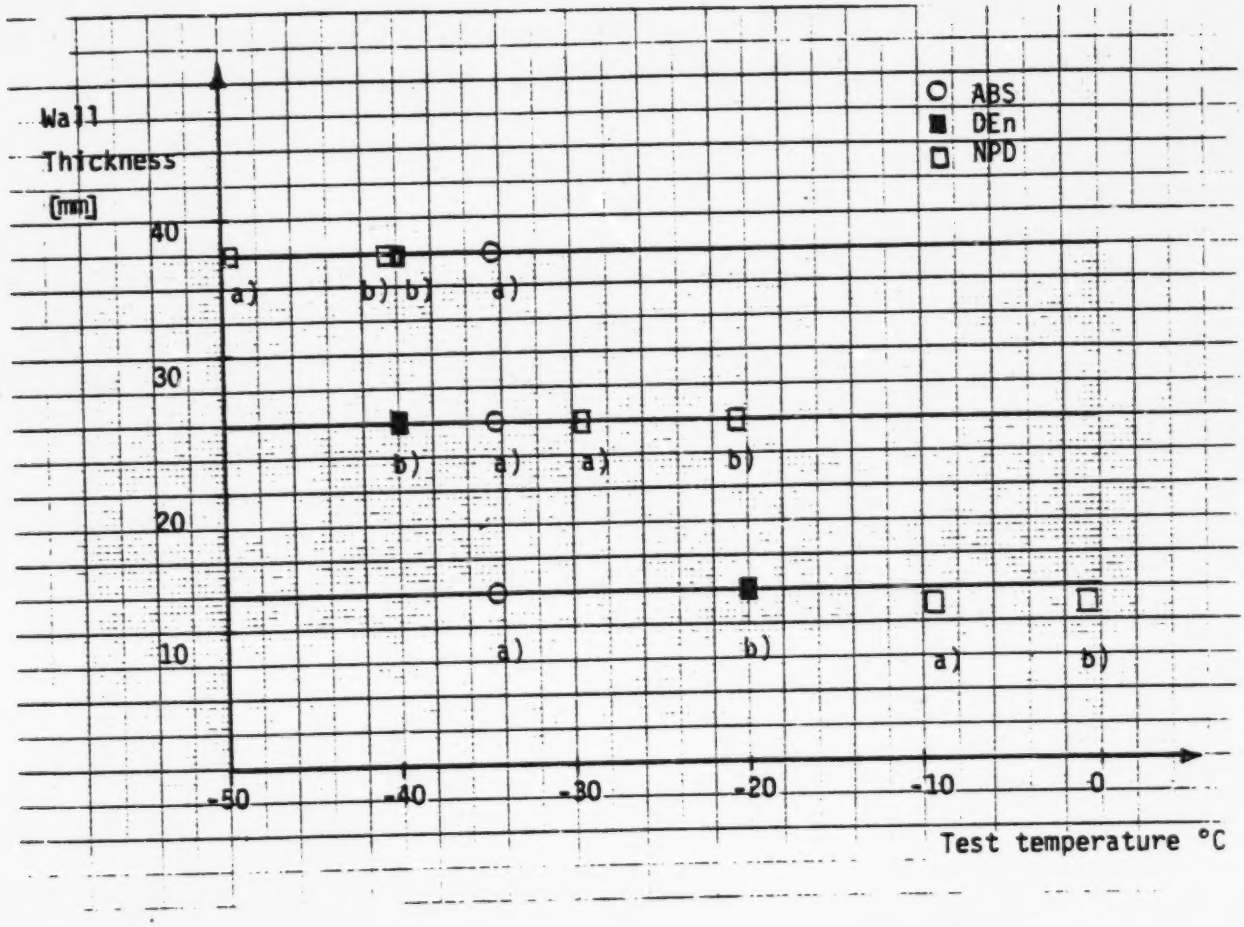
Temperature terms:

MDHT = Mean Daily High Temperature
MDMT = Mean Daily Mean Temperature
MDLT = Mean Daily Low Temperature

MMDHT = Monthly Mean of MDHT
MMDMT = Monthly Mean of MDMT
MMDLT = Monthly Mean of MDLT

MEHT = Monthly Extreme High Temperature
MELT = Monthly Extreme Low Temperature

Figure 15: Temperature Terms



a) Grand Banks

b) UK Waters

Figure 16: Test Temperatures, Code Examples

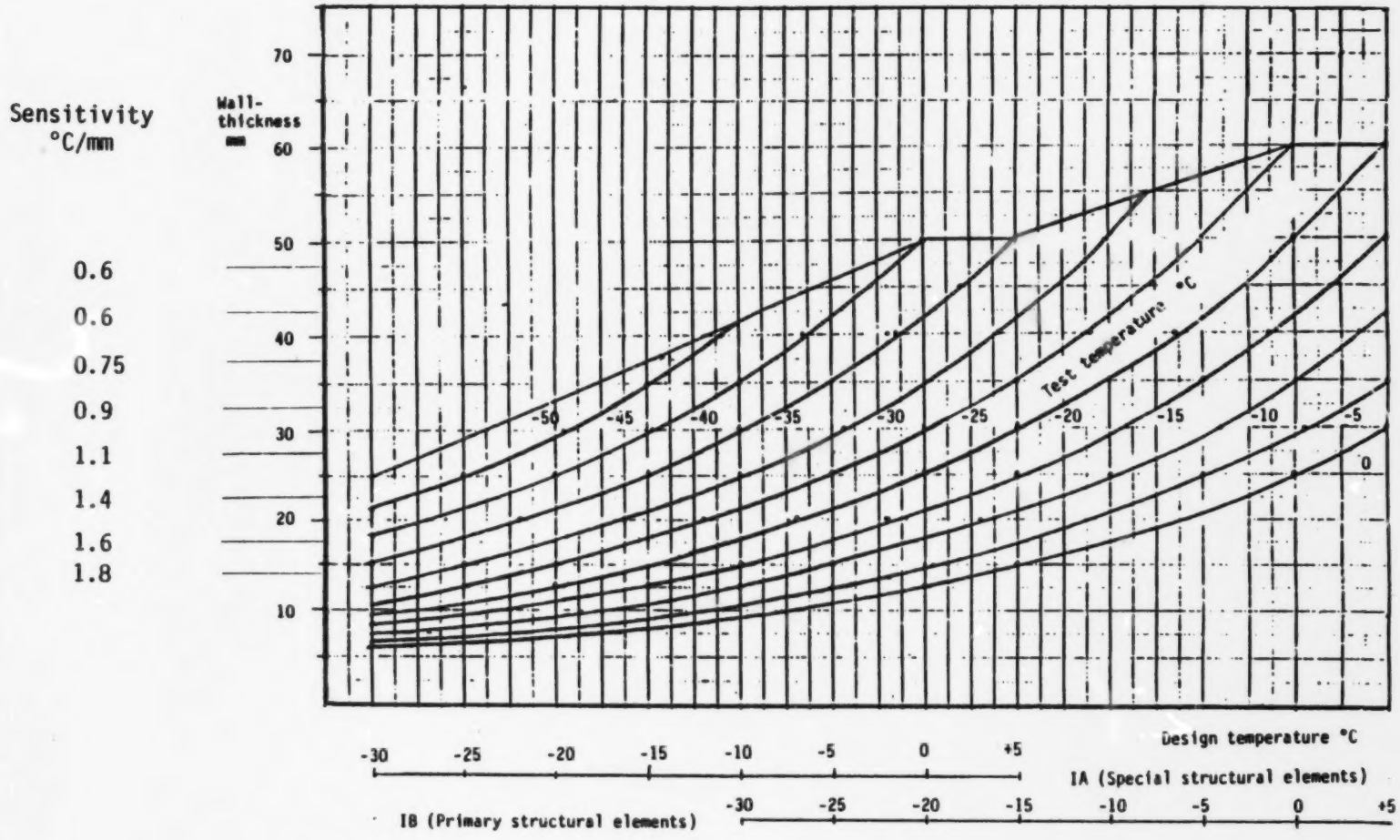


Figure 17: Thickness Sensitivity, Proposal

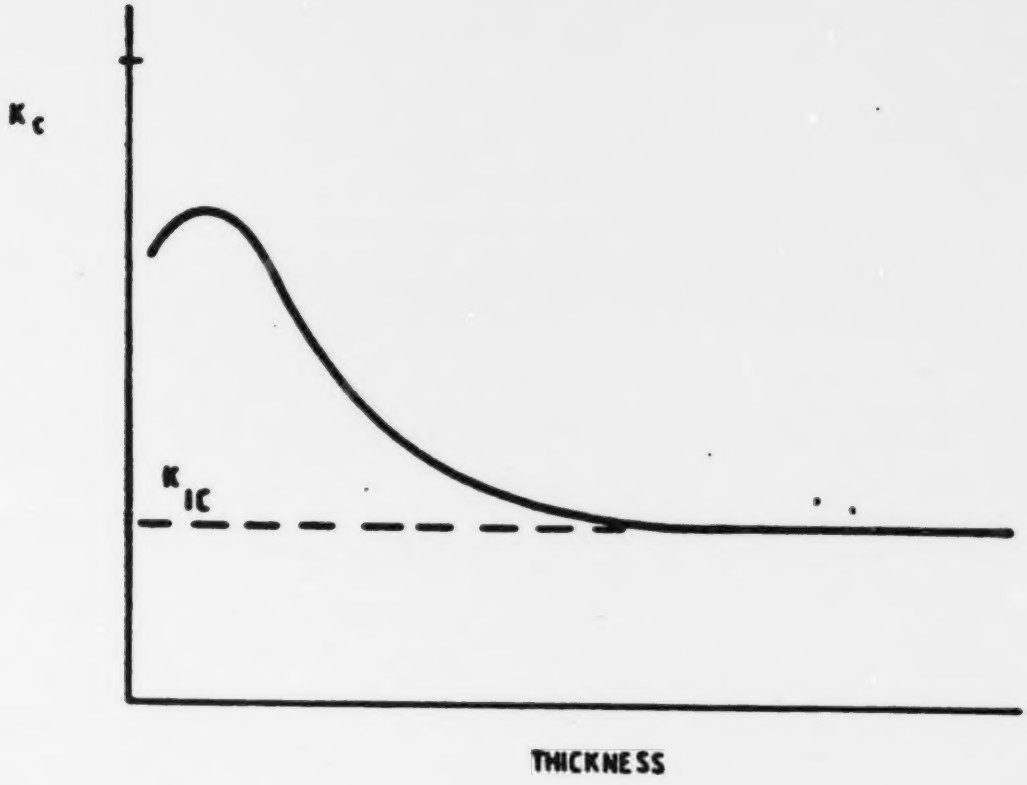


Figure 18: Fracture Toughness Variation with Thickness

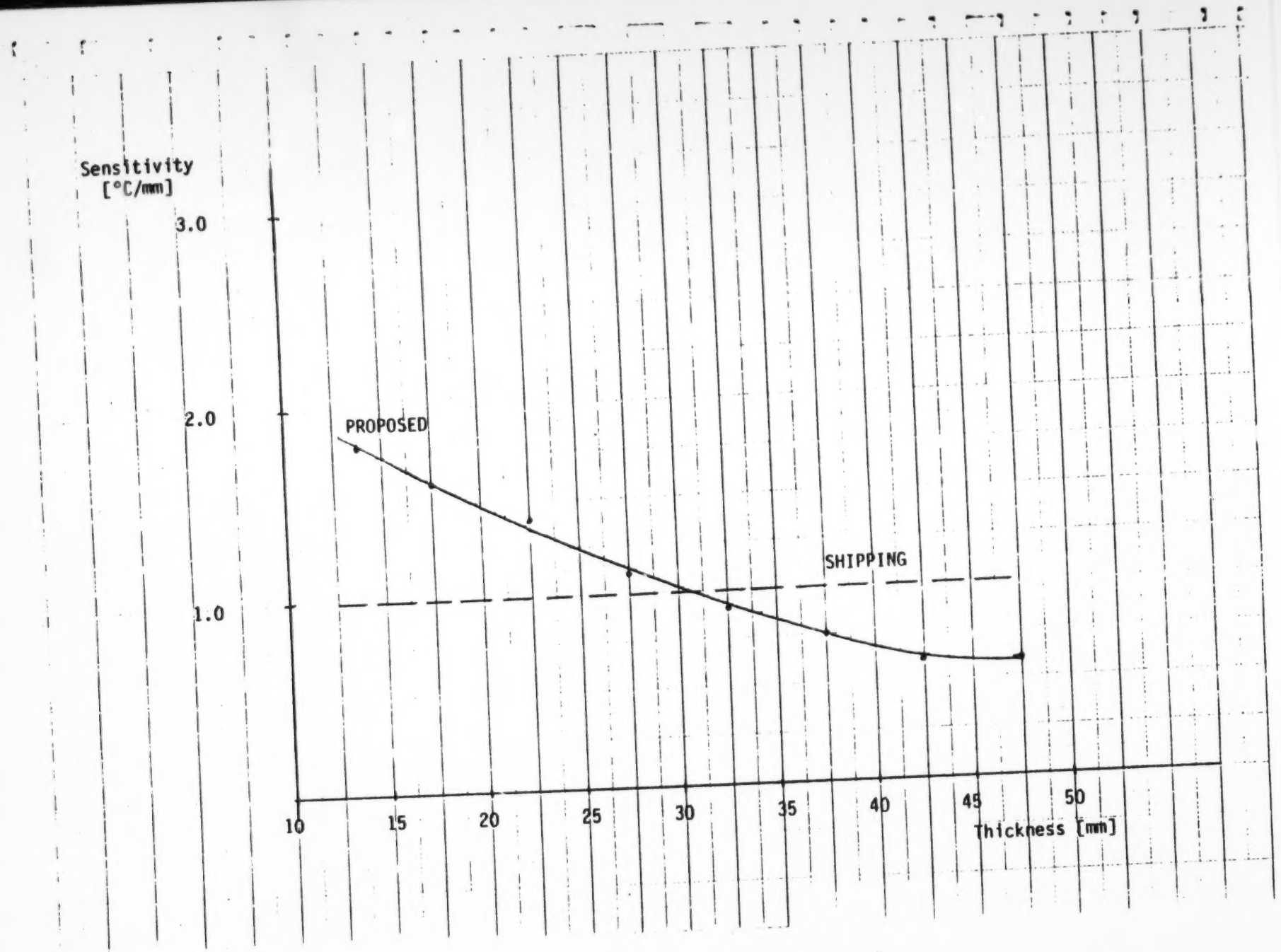


Figure 19: Thickness Sensitivity, Comparison

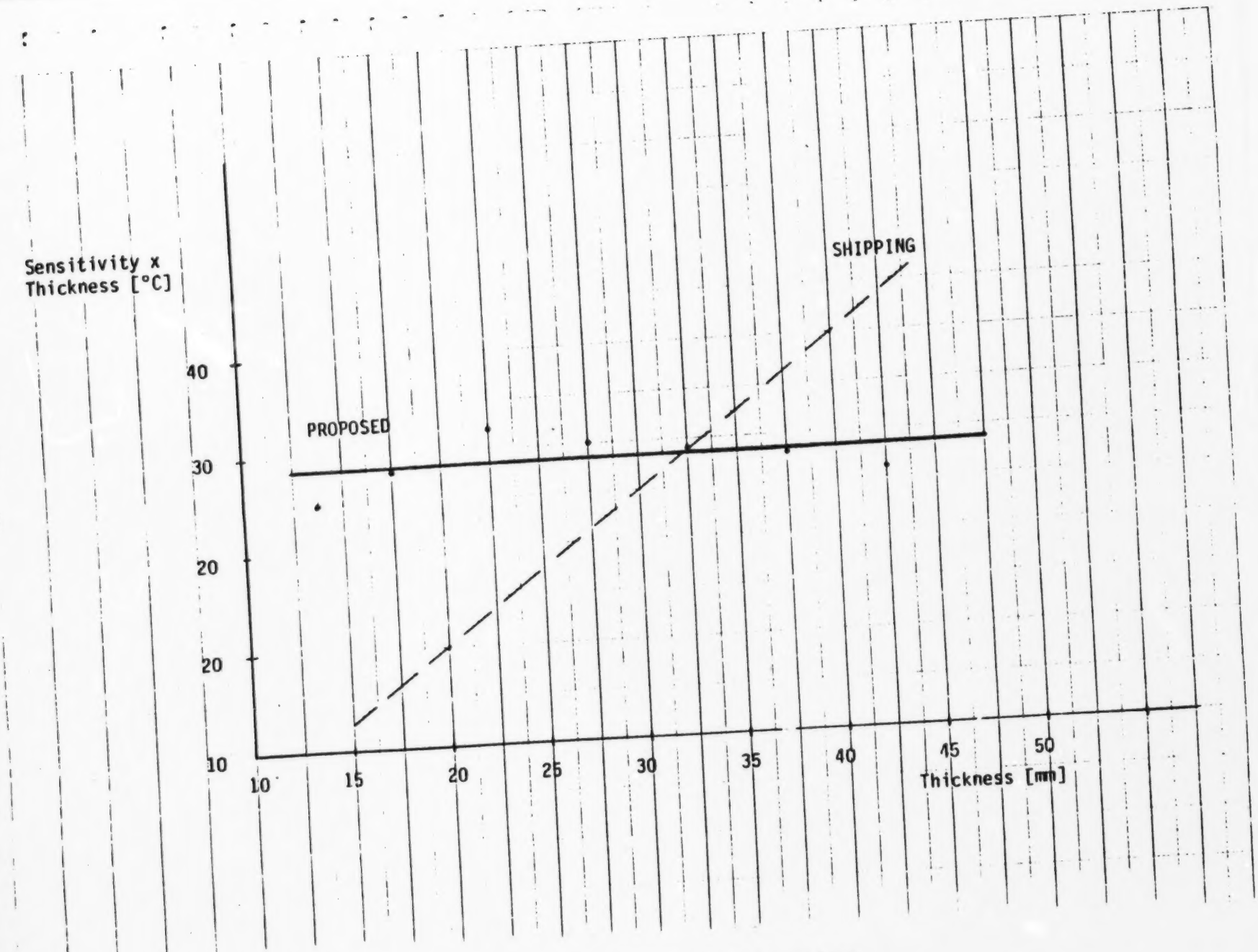


Figure 20: Thickness Sensitivity, Comparison

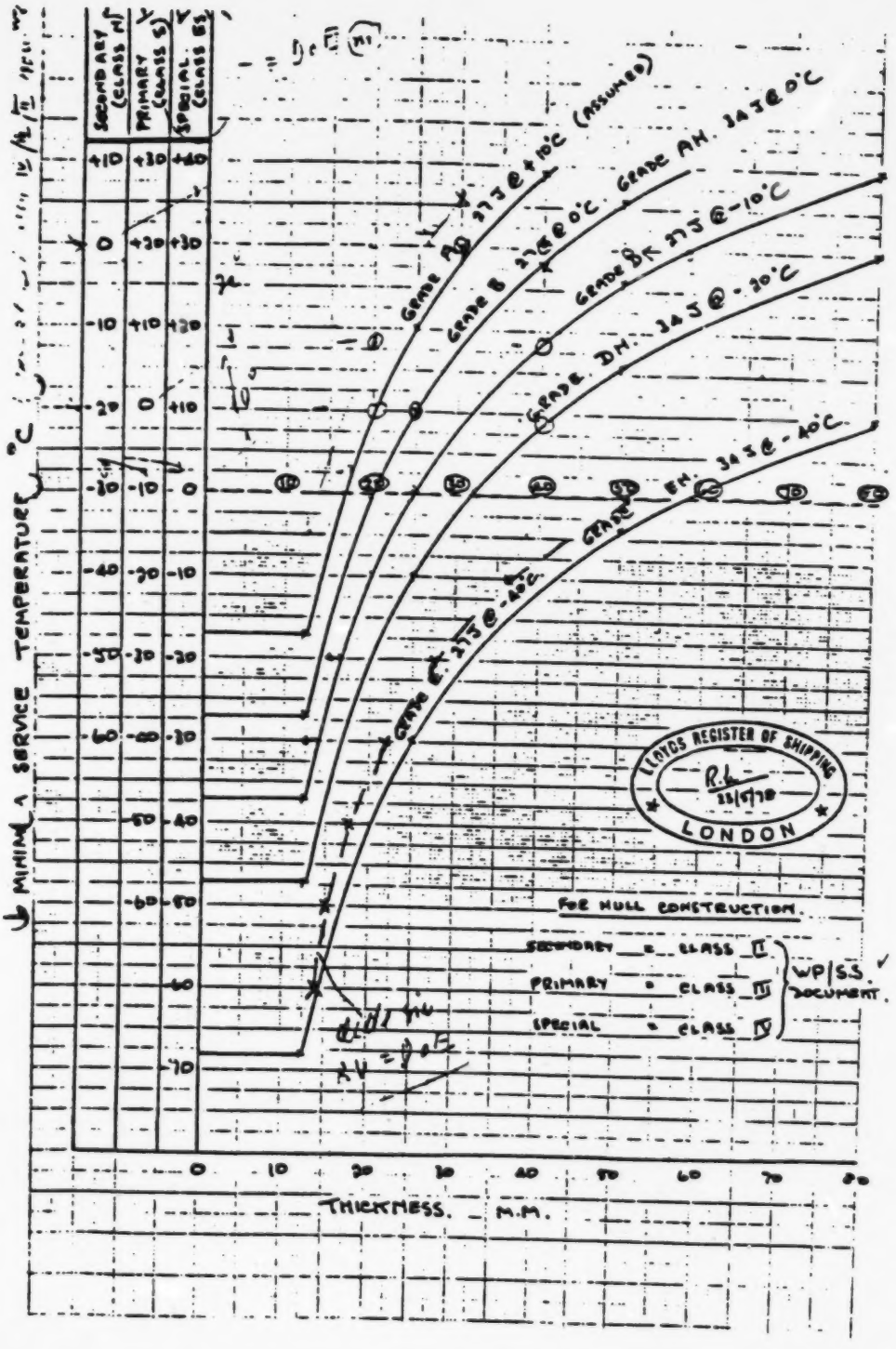
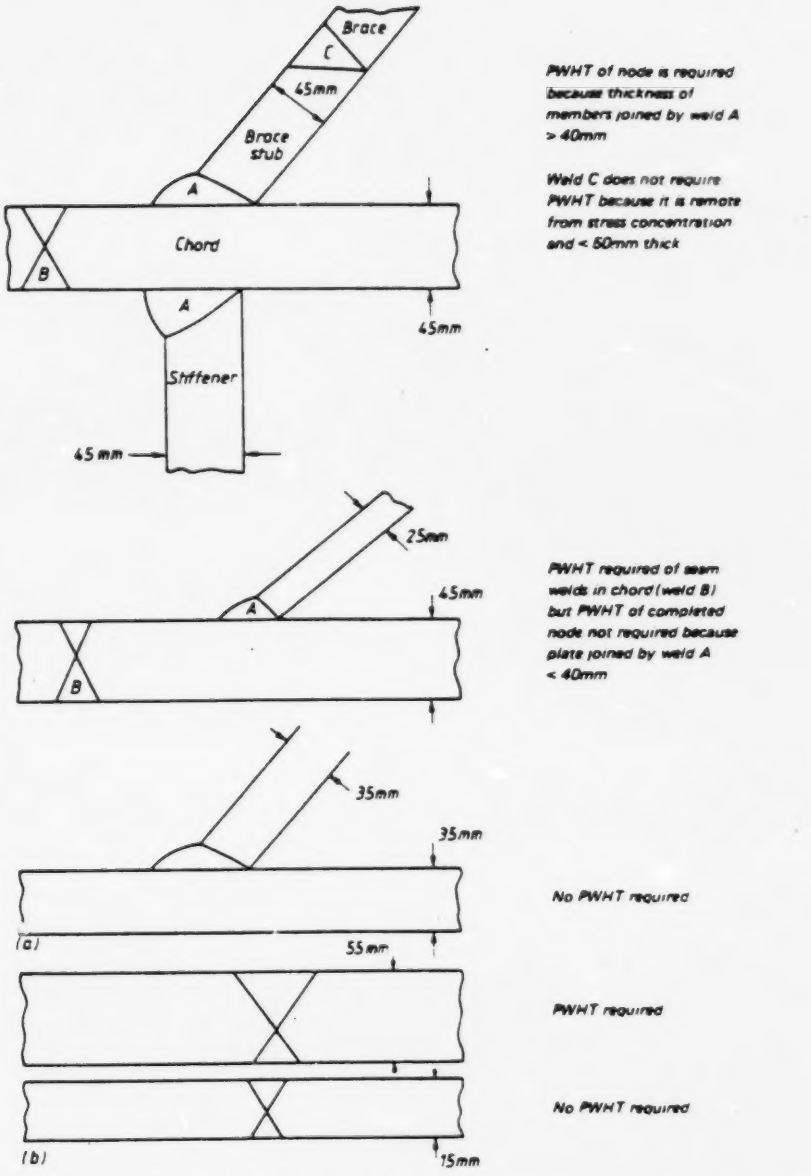


Figure 21: Thickness Sensitivity, Ship Grade Steels



Explanation of thickness governing PWHT requirements. (a) for welds near stress concentrations, (b) for welds remote from stress concentrations

Figure 22: Reference Thickness, PWHT

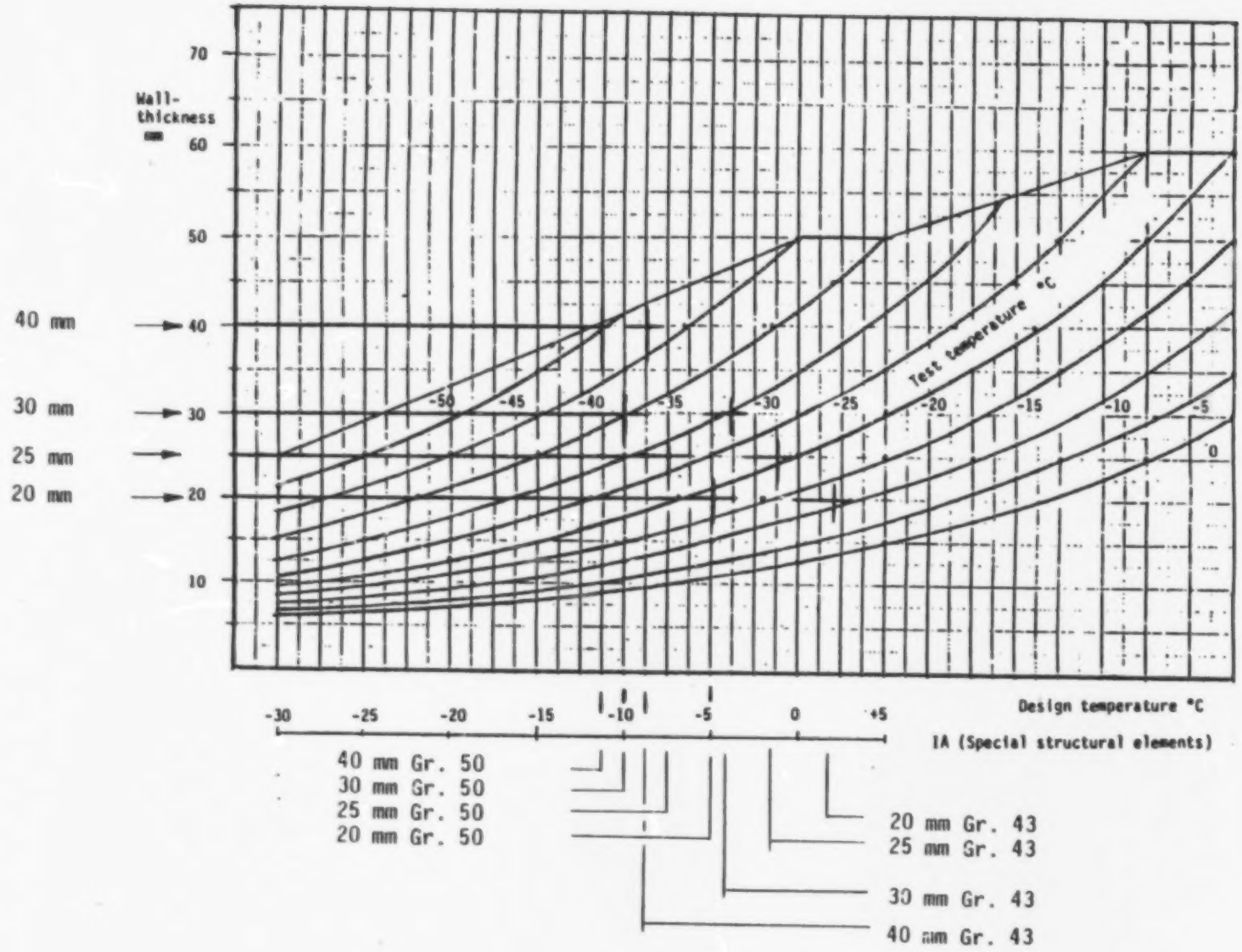


Figure 23: Test Requirements, BS Steels

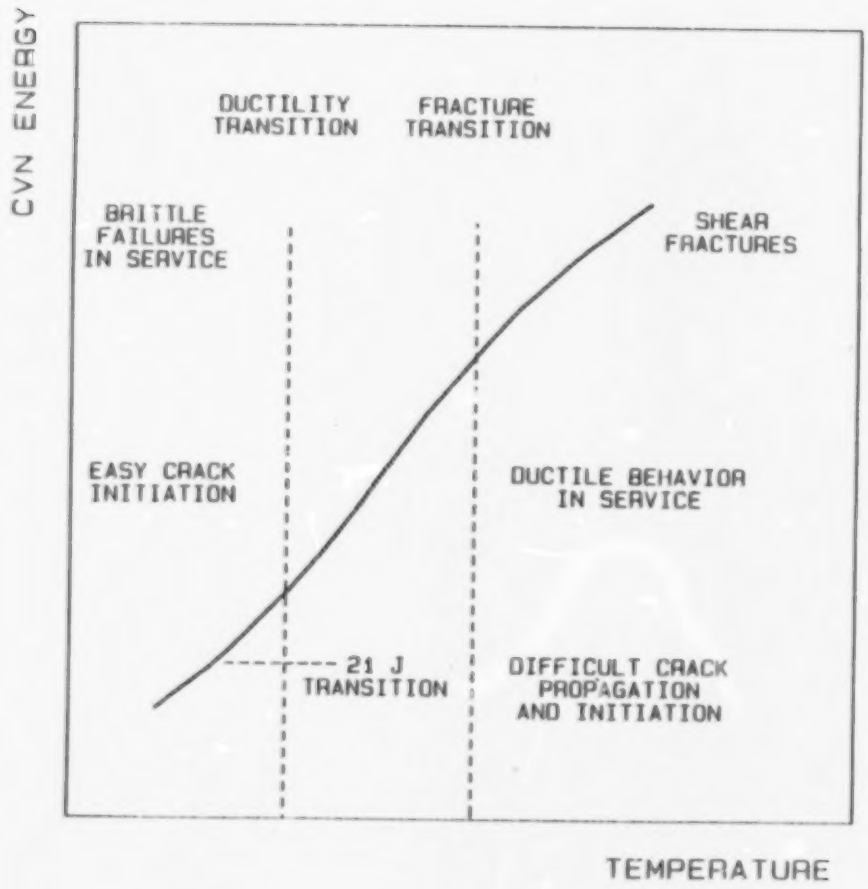


Figure 24: CVN Transition Curve, Service Experience